Essays in international finance

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[1]This thesis should not be reported as representing the views of Norges Bank. The views expressed are those of the authors and do not necessarily reflect those of Norges Bank.

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Overview

My first working day at Norges Bank took place only two weeks after Lehman Brothers failed in October 2008. The severity and the global nature of the financial crisis that followed the Lehman default meant a steep learning curve, but also valuable experience. Furthermore, the crisis triggered my interest in financial economics. I am grateful to Norges Bank for the opportunity to fully pursue this interest and thankful to many of my colleagues for their encouragement to begin this project.

My thesis consists of six independent articles organized as chapters. Although independent in nature, all the chapters are related to the impact of monetary policy, financial frictions and banking regulation on financial markets.

The banking sector has been subject to substantial regulatory changes over the past decade. A number of new regulatory requirements, ranging from increased capital buffers to higher liquidity standards and new reporting requirements, have gradually been phased in over the past ten years. These regulations have certainly influenced how banks are operating. At the same time, interest rates have plunged to unprecedented low levels yet the pressure on monetary policy to stimulate economic growth is larger than ever. As a result, some central banks have decreased the key policy rate below zero, engaged in various forms of guiding to the market on future policy and extensively expanded the central bank balance sheet to revive the economy. One lesson from the past decade with various unconventional central bank measures is that central banks indeed have powerful tools at hand with the potential to influence financial markets far beyond the short term interest rate.

In the midst of a new regulatory environment, the Libor benchmark rate, is at play. The Libor benchmark rate has been a cornerstone in the pricing of fixed income products for decades and serves as the underlying benchmark in financial contracts worth trillions of USD. After discovering that the Libor fixing had been manipulated over a long period, the Wheatley report, and later the Financial Stability Board (FSB), recommended to develop more stringent rules for the contributing bank. This recommendation was accompanied by a recognition of a need to develop alternatives to Libor. Recently, many jurisdictions have taken this a step further by recommending that Libor should not only be complemented, but indeed replaced by the alternative benchmark rates. Along with the measures taken by central banks, the transition to alternative benchmark rates have huge implications for market functioning and pricing and indeed interact with many of the new banking regulations in complex ways. In this thesis I explore some of the ways central bank measures, regulation and benchmark rates affect financial markets.

The first four chapters center around the foreign exchange (FX) swap market. The FX swap market enables market participants to hedge the foreign exchange rate risk arising from currency mismatch between assets and liabilities. FX swaps are characterized by deep market liquidity and high turnover. Due to the liquid nature and the fact that an FX swap implies changing one currency for another, this market responds fast to central bank measures across currencies and supply and demand changes caused by regulatory constraints.

The FX swap price is theoretically pinned down by the no-arbitrage condition referred to as Covered Interest Parity (CIP). CIP has been known as one of the most reliable no-arbitrage conditions in international finance. However, after the Global Financial Crisis in 2008, large and persistent deviations from commonly used measures of CIP has puzzled academics, market participants and policy makers alike.

Chapter 1, a result of joint work with Dagfinn Rime (BI) and Andreas Schrimpf (BIS), investigates the existence of potential CIP arbitrage by borrowing and investing in short-term instruments. Chapter 1 highlights that it is not arbitrary which money market instruments one choose when measuring CIP arbitrage and the choice of interest rates should be considered carefully. An important insight from this chapter is that measures by the central bank can have huge impact on banks' marginal borrowing and investment rates. Indeed, when the marginal costs of conducting the arbitrage is fully accounted for, only high quality banks face arbitrage opportunities. However, the persistence of arbitrage opportunities for high quality banks is still puzzling. We highlight that not only regulatory constraints, but also other institutional constraints make it possible for the arbitrage opportunities for the high quality banks to persist over time.

In chapter 2, joint with Ganesh Wiswanath-Natraj (WBS), we exploit FX swap order-flow and high frequency tick data to shed light on the price setting in the FX swap market. Guided by a small model we empirically test the price impact of order flow and how order flow responds to different types of information. The results suggest that the price impact of order flow has increased substantially after the global financial crisis. Investigating the post crisis period more closely, we find that the increase in price impact can mostly be attributed to periods of high funding heterogeneity in US dollar and over reporting dates when regulatory constraints are tighter. We also find that FX swap prices responds immediately to publicly available information like monetary policy announcements without a systematic impact on order flow, while private information affect order flow that eventually lead to price changes.

The third chapter look at potential real implications of deviations from CIP. Chapter 3 is based on work joint with Ragnar Juelsrud (Norges Bank), Artashes Karapetyan (ESSEC), Filippo Ippolito (UPF) and Jose Luis Peydro (Imperial). We exploit that Norwegian banks with access to US money markets faced lower implicit funding costs in Norwegian kroner by borrowing in USD and exchange for NOK with the FX risk fully hedged, compared to banks that borrowed domestically, during end of 2011 and beginning of 2012. This is a violation of the law of one price saying that similar assets should yield the same return across currencies. Within a difference-in-difference framework using granular loan and firm level data, we show that banks with access to foreign funding in this period supplied more credit and charged lower interest rates.Using firm-level data we trace out the impact of the expansion of credit on economic performance. We find that firms that borrowed from treated banks increased their fixed tangible assets, and in particular capital and fixed financial assets. The increase in borrowing from banks is driven by both an increase in short-term and long-term debt.

In chapter 4, I look at CIP in long-dated securities. This chapter builds on the insights from chapter 1. Central Bank measures have resulted in massive liquidity injection in some currency areas giving rise to large differences in liquidity premia across currencies. It is therefore necessary to use interest rates that capture these differences accurately when measuring deviations from CIP. While the results in chapter 1 suggested that some arbitrage opportunities remain in short-term securities even after accounting for interest rates that capture marginal costs, this is not the case in long-term securities. In short, my results indicate that the pricing of long term securities has been broadly in line with CIP also after the global financial crisis.

In Chapter 5, I turn the attention to the benchmark reform and the implications of replacing Libor. This chapter is based on joint work with Sven Klingler (BI). We are explaining the new benchmark rates across currencies and comparing them to Libor. In contrast to Libor, which is based on panel banks own assessment of uncollateralized funding costs across several maturities, the new benchmark rates are based on overnight transactions. Moreover, the new benchmark rates may either be collateralized or uncollateralized. We show that, depending of the nature of the new benchmark rates, regulatory requirements and the supply of high quality collateral affect the rates. We also pinpoint the issues connected to losing a term benchmark rate that includes liquidity and credit premiums.

Finally, in chapter 6, joint work with Dagfinn Rime (BI) and Gisle James Natvik (BI), we investigate the effects of conditional forward guidance on market participants forecast errors. Royal Bank of New Zealand, Norges Bank and Riksbanken were all early adopters of forward guidance, i.e. explicit communication of the future plans for the key policy rate. By communicating a conditional path of the interest rate going forward, these central banks explicitly inform market participants on actual policy going forward conditional on the assumptions of economic development. One important reason for doing this is to give market participants more information about the central bank reaction function. The question is if this information actually reduces market participants forecast errors, i.e. the difference between the projected market rate and the actual realization. We find that interest rates respond a great deal to central bank communication. However, the introduction of central bank interest rate projections has done little to improve these responses in the sense of bringing them closer to realized interest rates. Overall, central bank communication about future policy through interest rate projections has played only a limited role in guiding markets in the case of Sweden and Norway.

Acknowledgements This thesis is the result of collaboration with various co-authors. I have learned a lot from very competent co-authors and I would like to thank all of them for the collaboration, both professionally and socially. A special thank to Dagfinn Rime who I have collaborated extensively with and learned a lot from over many years. I would also like to thank Tom Bernhardsen, Arne Kloster and Ketil Johan Rakkestad for their unlimited support prior and throughout the process. Many of the ideas have been developed in company and conversations with Arne, Ketil and Tom. This thesis would not have been possible without them. Finally, many thanks to my family that has been forced to accept a long period with a father and husband not able to separate between work and leisure.

Chapter 1

Covered Interest Parity Arbitrage

1.1 Introduction

The persistent deviation from Covered Interest Parity (CIP) in major currencies, as some common measures indicate, has been one of the most puzzling phenomena in international financial markets in recent years.[1] The concept of CIP builds on the principle of 'no-arbitrage'—the most fundamental mechanism in financial markets. It postulates that it is impossible to earn a profit by borrowing in one currency and lending in another, while fully covering the foreign exchange (FX) risk. The pricing in money markets and in FX swaps should adjust so that it is not possible to reap risk-free profits (net of costs) on a self-financed strategy. Studying why a fundamental no-arbitrage relation such as CIP breaks down offers insights into the functioning of some of the world's largest and systemically important financial markets and the constraints faced by the key players operating in them.[2]

When it comes to arbitrage the devil is in the details. Testing the validity of a no-arbitrage condition such as CIP requires carefully accounting for the key costs and inherent risks in the arbitrage trade. Obviously, accounting for transaction costs is important. However, as we stress in this paper, it is even more important to account for the *marginal funding cost* the arbitrageur faces, and to make sure the trade is indeed *risk-free* from the arbitrageur's perspective. To understand the phenomenon, we zoom in on the key players, globally active banks, and describe how their incentives crucially depend on their funding costs.

Taking these considerations seriously in our empirical tests, we find that the no-arbitrage condition implied by CIP does in fact hold quite well for the majority of market participants—even though commonly used aggregate measures may indicate material arbitrage profits in recent years. As we show in this paper, the set of potential CIP arbitrageurs is fairly narrow, but with some high-rated globally active banks in a position to reap economically attractive arbitrage profits.

A situation with persistent arbitrage opportunities emerges as an equilibrium outcome in international money markets, when banks are heterogeneous in their U.S. dollar (USD) funding costs and funding liquidity premia diverge across major currency areas. An implication of different funding liquidity premia is that CIP cannot hold for different types of interest rates, e.g., both risk-free rates like repo-rates or rates with credit-risk like LIBOR-rates. We provide evidence based on FX swap order flow data consistent with such a market environment, and rely on issuance data on short-term USD funding instruments to show that CIP arbitrage opportunities are difficult to scale.

Before the Global Financial Crisis (GFC), Akram et al. (2008) found—based on carefully constructed high-frequency data from the interbank deposit market and taking account of transaction costs—that any CIP deviations were too small and short-lived to give rise to economically signifi-

[1] See, inter alia, BIS (2015), Barclays (2015), Pinnington and Shamloo (2016), Du et al. (2019), Shin (2016), BIS (2016), Borio et al. (2016a), Avdjiev et al. (2019), Arai et al. (2016), Duffie (2017a) and Debelle (2017).

[2] The key subject of study of this paper is the market for FX swaps—a derivative contract consisting of a simultaneous combination of a spot transaction and an opposite forward. FX swaps are traded OTC and are widely used by market participants to facilitate cross-border borrowing and investment and to manage exposure to FX risk. Banks use FX swaps for liquidity management in different currencies and the management of currency risk. By any standards, the FX swap market is huge with a daily trading volume exceeding U.S. dollar 3.2 trillion (BIS, 2019).

cant arbitrage profits. Since the onset of the GFC, however, sizable CIP deviations have emerged, even involving some of the world's most liquid currencies (such as the euro (EUR), the Japanese yen (JPY) and the Swiss franc (CHF)). The breakdown of no-arbitrage during the height of the GFC and of the European sovereign debt crisis—periods which saw price dislocations across many asset classes—may not be surprising.[3] However, e.g. Du et al. (2019) suggest that the anomaly has been particularly severe during the much calmer period since 2013. This stands in contrast to the above-mentioned pre-crisis evidence and (more generally) the basic principles of financial economics, and has puzzled academics, central bankers and market participants alike.

To make progress in the understanding of the CIP puzzle, we address how the main arbitrageurs would approach the question of whether it is attractive to enter into the trade. We focus on short-term (1-week to 3-month) arbitrage opportunities for global active banks, which we consider to be the arbitrageurs that matter at the margin. These banks operate in funding markets in multiple currencies, have broad access to short-term risk-free assets (including central bank facilities around the world), face constant funding/liquidity needs and can flexibly choose the cost-optimal funding option.[4]

In focusing on implementable arbitrage from the perspective of global banks, our approach deviates from the extant CIP literature in several important ways. *First*, we argue that it is critical to rely on money market rates that adequately capture fluctuations in banks' marginal funding costs. Against the backdrop of significant structural changes in money markets over the past decade, selecting the appropriate interest rates is not straightforward. There is a wide dispersion in short-term borrowing rates faced by participants in various segments in U.S. money markets (as shown, e.g., by Duffie and Krishnamurthy, 2016). Heterogeneity in funding costs (both across banks in USD money markets due to credit premia, and across major currency areas due to differences in funding liquidity premia) makes it impossible for a single FX swap rate to ensure that the 'law of one price' holds for the full spectrum of short-term interest rates. Such heterogeneity was not present pre-GFC as different rates lay virtually on top of each other, but has become a salient feature of today's money markets. Arbitrage incentives will hence differ substantially across banks and vary by their marginal funding costs. The law of one price will hold for one set of market participants, but not for others.

Second, we argue that it is important to treat the funding and investment leg of cross-currency arbitrage trades differently. For the funding leg, it is no longer appropriate to look at interbank rates

[3]For this reason we exclude crisis episodes, like the GFC (2008-9), the euro-crisis (2011-12), or the recent Covid-19 crisis.

[4]To be clear, while we consider non-banks to also respond to CIP deviations, they are not the major players that matter at the margin. Hedge funds, for instance, are dependent on bank funding (or prime brokered funding) to arbitrage price dislocations. Banks generally avoid charging their own customers below their own funding cost and hence would be reluctant to provide hedge funds with the leverage to profitably exploit any CIP deviations. Real-money asset managers (e.g. pension funds, central bank reserve managers or sovereign wealth funds) can be considered to be long-only investors and hence typically would not enter into leveraged arbitrage trades. Their search for cross-border value in investment options will also respond to pricing in the FX swap market, yet such opportunistic behavior cannot be regarded as arbitrage in the strict sense as it does not involve a full (self-financing) roundtrip.

such as LIBOR. Activity in interbank deposit markets has dwindled due to regulatory changes and excess liquidity created by central banks' asset purchase programs (e.g., Schrimpf and Sushko, 2019). Instead, it is necessary to turn to interest rates at which banks can raise wholesale money market funding from non-bank investors. We focus on Commercial Paper (CP) and Certificates of Deposit (CD), i.e. short-term unsecured funding instruments issued by banks that are typically held by U.S. prime money market funds (MMFs) or other institutional investors. In today's money markets, these rates are better at capturing the marginal funding costs of banks. We show that for CP rates (unlike for other interest rates), law of one price deviations are in fact fairly small—in stark contrast to, e.g., interbank offered (IBOR) or also risk-free rates (such as Overnight-Index-Swap (OIS) or repo rates).

Moreover, it is important to allow for the rate in the investment leg of the arbitrage strategy to differ from that in the funding leg so as to ensure that the trade is truly risk-free. As riskless investment vehicles we therefore consider both deposit facilities of foreign central banks and short-term government securities (T-bills). All market participants have access to the latter, but only a subset of globally active banks are central bank eligible counterparties and can deposit funds at the central bank deposit facility rate. T-bill rates will typically decrease in response to demand pressure generated by arbitrage, whereas the interest on reserves deposited at central banks is insensitive to volume.

Based on this empirical setup, we find that *risk-free* CIP arbitrage opportunities do indeed exist over our post-crisis sample period—but are confined to a small set of market participants. The vast majority of banks around the globe faces prohibitively high marginal funding costs in USD. Economically viable arbitrage opportunities are available only to those high-rated banks that have access to direct USD funding at attractive terms and can invest at the deposit facilities of foreign central banks. Such arbitrage opportunities are less attractive if short-term government securities are the only risk-free investment asset available (given that their interest rates tend to lie below the rate of remuneration on central bank deposit facilities).

Third, we study the main challenges for dealers of quoting FX swap rates against the backdrop of imbalances in the demand and supply of USD in the FX swap market.[5] Understanding the incentives faced by these key market intermediaries is crucial to explaining how the pricing anomaly arises and is not arbitraged away. We start by conceptually characterising the challenges faced by FX swap dealers in a situation when funding liquidity premia in different currency areas diverge. A situation like this has been an important feature of money markets in recent years due to the excess liquidity created by the balance sheet policies of major central banks outside of the U.S. (notably the Bank of Japan, the European Central Bank and the Swiss National Bank). While unsecured wholesale USD funding markets have remained costly and fragmented, with a large dispersion in

[5] FX swap dealers, the ones that actually set FX swap quotes, extract intermediation markups from the bid-ask spread, but have strong incentives to balance customer order flow. See e.g. Evans and Lyons (2002) on how FX dealers control inventory in the FX spot market. The basic principles also apply for simple derivatives such as FX swaps or forwards.

funding costs across banks, we show that funding liquidity premia have significantly compressed in other key currency areas (in particular, JPY, EUR and CHF). The main reason for this divergence has been the relative abundance of central bank reserve balances in the affected currency areas, compared to the U.S. where the Fed balance sheet was no longer growing and even shrinking.

We then study the impact of imbalances in the demand and supply for USD in the FX swap market—as captured via FX order flow—to gain a better understanding of FX swap market equilibrium and breakdown of CIP in this market environment. Relatively easier funding conditions outside of the U.S. create strong incentives for market participants to obtain USD funding via the FX swap market as opposed to raising such funding directly in U.S. money markets. To control inventory risk and to keep a matched book, a swap dealer that aims to balance order flow from customers needs to quote FX swap prices so as to incentivize flows in both directions. Consistent with this mechanism, we find that the price impact of swap order flow is particularly elevated in situations when the deviations from CIP are severe. By increasing the FX swap rate in response to net buying pressure to obtain USD through the swap, the FX swap dealer can control inventory by making it attractive even for banks of lower creditworthiness that have access to core USD funding markets to supply those USDs in the swap market. This essentially involves the granting of arbitrage profits for these counterparties. Importantly, the price impact of swap order flow is asymmetric. The impact of net flow pressure to obtain USD is large and statistically significant; net flow out of the USD and into currencies such as the JPY or the EUR, by contrast, only induces insignificant price changes in the FX swap market.

These results indicate that situations with large CIP deviations tend to coincide with broader funding constraints in U.S. money markets. Faced with the resulting demand and supply imbalances, swap dealers revise their quotes to attract providers of USD to take the other side. As a consequence, a confined set of market participants—notably, high-rated banks with access to core USD funding markets—will enjoy arbitrage opportunities. To our knowledge, this is the first paper investigating the role of order flow as a determinant of pricing in the FX swap market.

Finally, we complement the results from the order flow analysis by studying why such pricing distortions and arbitrage opportunities can persist for some time. Our goal here is to better understand some of the limits faced by potential arbitrageurs to scale up their positions. To this end, we rely on transaction-level data for short-term Certificates of Deposit issuances in USD funding markets. The pricing and availability of funding in these markets will determine how attractive and easy it is for the arbitrageur to benefit from the CIP deviations. Our regression results indicate that with reasonably large increases in issuance volumes, much of the CIP arbitrage profit quickly evaporates by the increase in USD funding costs. These results further support that funding constraints in USD are important to explain the existence of CIP arbitrage profit for a confined set of market participants and why these can persist.

Related literature. The GFC has revitalized research interest in the validity of CIP. A first wave of papers, e.g. Baba et al. (2008) and Baba and Packer (2009a), focused on the USD funding shortages of global banks as a key driver of the relationship's breakdown.[6] Based on this research, and more recently Bahaj et al. (2018a), a consensus emerged that the provision of USD liquidity via major central banks' swap lines with the Federal Reserve was instrumental in alleviating the USD shortage and helped to significantly ease the CIP dislocation.

Our paper mostly relates to a second wave of research that seeks to explain why deviations have been so persistent post-GFC—even in the absence of any obvious market stress. Du et al. (2019) carefully document the price dislocations, stressing in particular the importance of bank regulations, and suggest a causal link from regulation to CIP deviations. Sushko et al. (2016) highlight the role of FX hedging demand. Cenedese et al. (2017) use trade repository volume data to study limits to arbitrage and to study imbalances in the dealer-to-customer segment of the FX swap market. Iida et al. (2016), Wong and Zhang (2018) and Wong et al. (2016) stress the importance of counterparty risk.

Furthermore, our paper relates more broadly to work emphasizing the role of intermediation frictions and the role of limits to arbitrage. Gabaix and Maggiori (2015) provide an equilibrium model where intermediation frictions and segmentation effects can lead to the failure of both uncovered and covered interest parity. The results in our paper are also linked to theoretical work emphasizing the constraints faced by arbitrageurs in segmented markets (e.g. Gromb and Vayanos, 2002), frictions in funding markets (e.g. Brunnermeier and Pedersen, 2009; Gârleanu and Pedersen, 2011) and slow-moving capital (e.g. Mitchell et al., 2007; Duffie, 2010).

Finally, although our approach differs from other current papers, our focus on funding liquidity differences across currency areas and heterogeneity across banks in terms of funding costs has antecedents in some of the earliest work on CIP. Tsiang (1959), for instance, emphasizes that being liquid in crucial currencies like the USD is valued differently than being liquid in another. Both Tsiang (1959) and Branson (1969) stress the importance of heterogeneity across the banks that are the key arbitrageurs in the forward exchange market. Following this tradition, we point to banks' marginal unsecured funding costs as the main source of heterogeneity and ability to arbitrage the CIP condition.

The rest of the paper is structured as follows. Section 1.2 lays out the main concepts and provides some basic stylized facts going back to before the GFC, while the implied data requirements are spelled out in Section 1.3. Section 1.4 investigates law of one price violations and CIP arbitrage in international money markets based on a realistic assessment of marginal funding costs. It focuses on the heterogeneity of banks' borrowing costs in the commercial paper market and quantifies the magnitude of riskless cross-currency arbitrage profits. Section 1.5 explores equilibrium dynamics in the FX swap market from a dealer's perspective in a world with segmented money markets and

[6] Other important contributions include Coffey et al. (2009), Gârleanu and Pedersen (2011), Goldberg et al. (2011), Griffoli and Ranaldo (2010), McGuire and von Peter (2012), Bottazzi et al. (2012), and Syrstad (2014).

divergence in liquidity premiums across currency areas. It presents results on the price impact of order flow and explores the forces that impede arbitrage. Section 1.6 concludes. A separate Online Appendix contains supplementary material.

1.2 CIP arbitrage: concepts and stylized facts

This section defines some key terms and provides an overview of relevant stylized facts. It also shows that the choice of interest rates is a non-trivial, yet crucial, input for the study of CIP violations.

1.2.1 CIP vs. LOOP

We distinguish between two key concepts—the no-arbitrage condition known as Covered Interest Parity (CIP) and the Law of One Price (LOOP). Our focus is on CIP, but to understand dynamics in the FX swap market, it will be necessary to refer to LOOP as well.

Covered interest parity. CIP is based on the basic proposition that a *self-financed, risk-free* arbitrage trade—borrowing in e.g. USD, investing in a risk-free asset in e.g. EUR, and using an FX swap in order to ensure riskless conversion of the proceeds—should not yield any profits.

To exploit CIP deviations, the arbitrageur has to perform a full *round-trip* of trades:

1. Borrow USD for, say, 30 days, at rate $r_{t;\$}$ directly in U.S. money markets

2. Sell USD against EUR spot to obtain $1/S_t$ EUR; simultaneously enter a forward F_t, reversing the currency exchange at a predetermined price in 30 days (effectively entering a FX swap contract),

3. Invest the EUR at the currently available 30-day EUR rate $r_{t;\star}$ in EUR money markets.

4. At maturity, repay the USD debt, $\left(1 + r_{t;\$}\right)$.

The (zero-profit) no-arbitrage condition defines the relation known as CIP. A requirement is that all transactions (borrowing, spot, forward and lending) are made simultaneously and hence the profits are known ex-ante (we therefore drop time subscript henceforth). The forward contract removes the FX risk, and, if the interest rates in the investment leg are risk-free, this will amount to a risk-free (self-financed) arbitrage trade. Arbitrageurs typically implement the spot-forward combination via an FX swap since the swap market is more liquid than the outright forward market (e.g. BIS, 2019).

It is also quite common to refer to the arbitrage profits as *cross-currency basis*, defined as follows:

$$Basis = \frac{F}{S}\left(1 + r_\star\right) - \left(1 + r_\$\right), \tag{1.1}$$

that is, the discrepancy between the synthetic interest rate implied by the FX swap $\frac{F}{S}(1+r_\star)$ and the direct interest rate $(1+r_\$)$. A higher basis, as defined here, corresponds to a situation where the USD trades at a premium in the swap market compared to raising funds directly in U.S. money markets.[7]

In reality, the arbitrageur will encounter transaction costs in form of bid-ask spreads. In the example above, she will borrow at ask rates, lend at bid rates, buy spot at ask (EUR is the base currency in EURUSD exchange rate), and sell forward at the bid. No-arbitrage then holds if the borrowing rate (in USD in the example above) is equal or higher than the implied lending rate in the same currency:

$$\left(1+r_\$^a\right) \geqslant \frac{F^b}{S^a}\left(1+r_\star^b\right), \tag{1.2}$$

where the superscripts a and b symbolize ask and bid rates, respectively, and $r^a > r^b$.[8]

Law of one price violations. The basic law of one price condition in international money markets implies that borrowing costs in similar funding vehicles should be equal across currencies. To assess deviations from LOOP, we compare the *direct* borrowing costs in currency A money markets with the *implied* borrowing costs (based on the FX swap market). The latter are given by the costs of raising funds in e.g. U.S. money markets, converting the funds into e.g. EUR while at the same time hedging the currency risk. While, in this paper we mainly focus on a funding perspective of LOOP, one can also take an investment perspective by comparing the investment return in currency A with that on a synthetic asset (i.e. the implied investment return based on currency B hedged back into currency A).

There are some important differences between testing for LOOP vs CIP violations. LOOP deviations represent an opportunity for borrowers to fund a *given* position in an asset more cheaply by raising funds in another currency and hedging the FX risk via the FX swap market. In other words, responding to LOOP deviations does not require an expansion of balance sheet, but is just akin to a recomposition of the funding (or investment) mix. While some authors refer to this as borrower's arbitrage, we deem it more appropriate to characterize such behavior as exploiting "relative value" opportunities. By contrast, exploiting CIP deviations leads to an expansion of the arbitrageur's balance sheet as the strategy needs to be leveraged, thereby requiring funding.

1.2.2 Stylized facts about international money markets

Akram et al. (2009) showed that CIP held closely in a pre-GFC sample when calculated using high-frequency interbank deposit rates. These rates are of similar type as LIBOR-rates which were the

[7] We prefer to define the basis this way, given the more straightforward link to arbitrage strategies borrowing directly in U.S. money markets. Note that other papers sometimes define the basis the other way around (e.g. Du et al., 2019).

[8] For further details on measurement respecting all market conventions, see Appendix B and Online Appendix 1.A.

common choice in prior tests of the validity of CIP. Figure 1.1 plots the basis using one-week LIBOR-rates for GBP and JPY against USD from 2004. The figure confirms that the LIBOR basis was close to zero pre-GFC, but that large deviations emerged after the GFC (as also documented elsewhere). Prior to the GFC, the average 1-week LIBOR-basis was 2bp (Sterling) and 1.4bp (Yen) and hence quite negligible. Post-crisis (after 2013), however, the same basis had risen to 12bp (Sterling) and 23bp (Yen) on average—a notable shift compared to pre-crisis.[9]

[Insert Figure 1.1 about here]

Prices of FX swaps (as implied by the so-called swap points) are determined by the dealers of the large investment banks, aiming to earn the bid-ask spread from their intermediation services while maintaining a balanced book (i.e. a zero overnight inventory). If the dealer does not succeed in keeping inventory close to zero, funding has to be raised from the bank's Treasury unit to cover the imbalance. Such funds are not costless, but internally priced reflecting the banks' funding cost. What this boils down to is that the dealer generally cannot quote FX swap prices to counterparties that would imply a price below the bank's own internal funding costs.

The fact that the LIBOR cross-currency basis was close to zero before the GFC suggests that banks' funding costs over this period were closely approximated by LIBOR. However, after the GFC, the interbank deposit market (i.e. the market underpinning LIBOR) is no longer a primary source of term funding for banks. Figure 1.2, Panel (a), shows that the activity in U.S. interbank markets has decreased substantially post-GFC.[10] At the same time, dispersion in banks' funding cost, e.g. as proxied by dispersion in submissions to the LIBOR-panel, has increased notably suggesting that LIBOR is no longer a representative rate that would uniformly capture major banks' funding costs. U.S. prime money market funds have strengthened their function as important marginal funding source for banks, and Panel (b) shows that the U.S. Money Market Fund reform of 2016 was a major impediment to this source of funding (more on this below). Hence, post-GFC it is critical which money market rates are used to capture banks' marginal funding costs and that dealers draw on when pricing of the FX swap.

[Insert Figure 1.2 about here]

It is also interesting to take a longer-term perspective on the cross-currency basis for risk-free rates, which are not exposed to the credit premia as embedded in unsecured rates such as LIBOR. One type of risk-free money market rates are generalized collateral (GC) repo rates (where the basket of possible collateral consists of U.S. Treasury securities), while another such rate are T-Bill rates.[11] Figure 1.3 plots the cross-currency basis calculated from repo and T-bills over the same sample period and currencies as shown before for the LIBOR-basis.

[9] Small deviations in the LIBOR-basis can be attributed to the LIBOR being fixed at 11 am GMT while the FX swap price is the closing price at 7 pm CET.

[10] Similar trends can be observed in other currency areas, (see,e.g. ECB, 2015; Schrimpf and Sushko, 2019).

[11] To be sure, T-bill rates are not capturing funding costs for arbitrageurs, but T-Bills are suitable instruments for market participants exploiting LOOP deviations (from an investment perspective).

[Insert Figure 1.3 about here]

What is notable is that the cross-currency basis using risk-free interest rates also shows considerable deviations in the pre-GFC period—in strong contrast to the LIBOR-basis. Pre-GFC, the 1-week repo-basis reached 10bp (Sterling) and 12bp (Yen) on average, and it only picked up slightly post-crisis to reach 14bp (Sterling) and 15bp (Yen) after 2013. In a similar vein, pre-GFC we observe LOOP deviations for T-Bills of magnitudes not too different from those in the post-crisis: 23bp (pre-GFC) vs 15bp (post-2013) for Sterling, and 33bp (pre-GFC) vs and 39bp (post-GFC) for Yen.

Figure 1.3 demonstrates that deviations from the law of one price for risk-free rates are not an entirely new phenomenon. The underlying drivers hence cannot solely be attributed to factors that changed post-crisis (such as a tightening of banking regulation). One such factor that had also been present then is the special investor preference for U.S. Treasury securities, due to their safety and liquidity features. It is commonly accepted that this preference gives rise to a "convenience yield" and a depressed U.S. T-bill rate (Krishnamurthy and Vissing-Jorgensen, 2012). And indeed, already Tsiang (1959) in some of the earliest work on CIP, pointed out that if potential arbitrageurs value assets with similar characteristics denominated in different currencies differently, e.g. due to convenience yields, deviations from LOOP in international money markets can arise. A similar argument can be applied to the repo-basis. Raising funds through a repo encumbers high-quality collateral such as U.S. Treasury securities. Just like the T-bill basis may be non-zero because of differences in convenience yield, the repo-basis may be non-zero due to cross-currency differences in how investors perceive the collateral value of the Treasury securities.[12] This means that there will be a link between the T-bill basis and the repo-basis.[13]

The discussion above shows how important it is to use interest rates that capture arbitrageurs' marginal funding costs when analysing CIP. LIBOR-rates used to fit this bill pre-GFC, but do not do so anymore. Neither T-bill and repo rates capture banks' marginal funding costs, and a law of one price deviation observed for such rates does not necessarily signal the existence of a "free lunch."

1.3 Data

Unless otherwise stated, we focus on the post-crisis period from the beginning of 2013 (after both GFC and the euro crisis), a period of calm financial markets, where explaining CIP deviaions has proven particularly challenging. The dataset ends in June 2017. Our study comprises the set of most liquid currencies worldwide, that is, the Australian dollar (AUD), the Canadian dollar (CAD),

[12] We provide a more detailed analysis of trading strategies involving repos and another risk-free interest rate, Overnight Index Swaps, in Online Appendix 1.D and 1.C.

[13] **?** illustrate this point by using repo (and reverse repo) rates for different currencies from a Eurex trading platform where the collateral is of the *same* currency, i.e the funding leg involves a special repo where the collateral is denominated in foreign currency. This approach in turn eliminates the difference in the financing costs across currencies. They find that measures of law of one price deviations for repo rates based on the same collateral are close to zero.

the euro (EUR), the British pound sterling (GBP), the Japanese yen (JPY), and the Swiss franc (CHF), all quoted against the U.S. dollar (USD). We consider three tenors: 1-week, 1-month and 3-month (with special emphasis on the 3-month tenor unless there are important lessons to be made from the short tenors). These tenors are the most liquid and natural choices to implement CIP arbitrage.

1.3.1 The funding leg of CIP arbitrage

Unlike in the textbook description of CIP, there is a plethora of money market rates faced by different types of market participants and with very different characteristics.[14] As shown by Duffie and Krishnamurthy (2016), the dispersion across different types of rates has increased substantially post-crisis. Against the backdrop of structural changes in funding markets and a large degree of fragmentation, care needs to be exercised to select rates that most adequately capture the marginal funding costs of the critical arbitrageurs in international money markets (i.e. global banks).

Neither LIBOR, repo or T-bill rates qualify as adequately capturing banks' marginal funding costs in the post-GFC world, as discussed in the previous section. Instead, money market instruments such as Commercial Paper (CP) or Certificates of Deposit (CD) have emerged as the key marginal sources of obtaining term funding for banks. CPs are issued with maturities up to 9 months, while CD maturities can also be longer. These instruments are typically held by non-banks, such as money market funds or other institutional investors, and provide a flexible way for banks to attract short-term unsecured funding. There is substantial heterogeneity across banks' funding costs in CP and CD markets. High-rated banks (A-1/P-1 rating) pay significantly less for USD funding than mid-rated banks (A-2/P-2 rating) or lower-rated banks.[15]

Our analysis of CDs also draws on primary market issuance data. We collect all USD CD issuances with maturity close to 1-month, 3-month and 6-month maturity, giving us a large cross-sectional variation in funding rates. However, this comes at the cost of slightly fewer time series points as we only have data from issuances available. For our analysis of arbitrage profits, we hence primarily use CP rates for which we have a more complete time series. The virtue of the granularity of the CD data is that it allows us to study the dispersion in funding costs across institutions and the relationship between issuance volume and funding cost. The dataset (obtained from Bloomberg) includes issuances by most of the major global banks, with precise information on the date of issuance, volume and yield.[16] After filtering out non-rated small banks (mostly local U.S. banks), and aligning our sample with the rest of our analysis (January 2013 to June 2017), we are left with around 17,000 observations.

[14] Table 1.8 in Appendix A gives an overview of our data.

[15] Results for the best rating group, A-1+/P-1, are qualitatively similar to the results of A-1/P-1 and available on request. We leave out this group for reasons of space and because it is a narrower set of banks with fewer observations. Figure 1.7 in the Online Appendix compares results for A-1/P-1 banks to A-1+/P-1 banks. We refer to A-2/P-2 banks as mid-rated as there are many banks with international operations with a lower rating (or no rating at all).

[16] CD issuance requires that the issuing bank be located in the U.S., either by subsidiary, branch or head office.

Descriptive statistics for money market rates at the funding leg. Table 1.1 reports descriptive statistics for 3-month CP spreads (for two rating categories) over OIS rates (Table 1.H.1 in the Online Appendix shows the same descriptive statistics for 1-week and 1-month maturity). OIS rates are commonly regarded as a proxy for risk-free rates; they are insensitive to fluctuations in term funding liquidity premia and thus cannot represent the *marginal* funding costs of the typical arbitrageurs when funding conditions change.[17] For the sake of comparison, we also include interbank deposits and IBOR rates over OIS rates in Panels B and C.

Table 1.1 Panel A shows that there are notable difference in funding costs across banks for different rating categories, and across currency areas for the same rating category. For 3-month USD funding, mid-rated banks on average pay about 14bps more than high-rated banks. Moreover, the table shows that over the sample period USD funding was on average significantly more expensive than funding in other major currencies (for the same rating bucket). The difference is especially stark in case of the JPY: a high-rated bank can fund itself about 43bps more cheaply in JPY as in USD markets—illustrating the difference in funding liquidity premia across the two currency areas. Even though IBOR and inter-bank deposit rates are less suitable to capture banks' marginal funding costs post-GFC, the descriptive statistics shown in Panels B and C corroborate the picture of notable differences in funding costs across currency areas.

[Insert Table 1.1 about here]

Time-variation in funding costs. Figure 1.4 shows the evolution of 3-month USD CP and CD spreads over time. All spreads are positive, with the volume-weighted CD rates being more volatile. The vertical line marks the implementation of U.S. Money Market Fund (MMF) reform on October 14, 2016.[18] The reform can be considered as a severe disruption to USD funding—the drop in prime funds' assets under management in the run-up to reform implementation (see Figure 1.2b) effectively led these funds to scale back on their provision of USD funding through purchases of banks' short-term debt. As can be gleaned from Figure 1.4, for both high- and mid-rated banks, the CP spread increased notably in this episode. Given their reliance on CP/CD funding from MMFs, especially non-U.S. banks saw a worsening of their USD funding situation. It is also important to note that the funding strains in 2016 were exclusive to USD markets, but were not present in other major

[17] Overnight Indexed Swap (OIS) contracts are derivatives that involve exchanging a fixed interest rate against a pre-defined floating overnight rate. The instruments are used for hedging purposes, but not for raising funds. Since the overnight rate usually contains a negligible credit risk premium (due to the very short term) and a majority of central banks target the overnight rate, this rate is usually close to the key policy rate. An OIS contract does not involve any exchange of the principal (as it is a derivative), only the net difference between the realized overnight rate during the term of the contract and the agreed fixed rate. Figure 1.H.1 depicts the OIS-basis for the currency pairs in our sample.

[18] MMF reform induced two main changes which made prime funds much less attractive for investors: i) a requirement to publish mark-to-market values of assets in contrast to the constant asset valuation previously used, and ii) a possibility for the fund to impose a redemption fee of 2 per cent if the assets that can be liquidated within one week fall below 30 percent of the fund's assets or stop all redemptions for up to 10 days if the threshold of 30 per cent is breached.

currency areas.[19]

[Insert Figure 1.4 about here]

1.3.2 The investment leg of CIP arbitrage

The main economic prediction of CIP is that risk-less arbitrage profits from borrowing and investing in international money markets and FX swap markets should be zero (once the relevant costs are factored in). In the analysis of cross-currency arbitrage in international money markets, it is therefore important to choose interest rates in the investment leg that are risk-free. Obviously, lending rates to other banks do not fulfill this criterion. Academic work on CIP deviations prior to the GFC often considered unsecured rates such as IBOR for the *investment leg* of CIP arbitrage trades—a perspective which is not warranted due to credit risk. We hence deviate from prior work on CIP by considering an interest rate for the investment leg of the arbitrage trade that differs from that for the funding leg.[20]

As risk-free investments, we hence turn to government T-bills (bid quotes) and central banks' (CB) deposit facilities. The main difference between the two instruments is that the former is widely accessible to all market participants (including non-banks), whereas the latter is only available to the eligible counterparties of the central bank (i.e. banks). Moreover, the CB deposit rate is in most cases unresponsive to the amount of reserves placed in the facility.[21] By contrast, T-bill rates fluctuate with changes in demand and supply conditions. Table 1.2 shows that the rate on T-bills often lies below the OIS-rate and that the CB deposit rate is therefore relatively more attractive.[22]

[Insert Table 1.2 about here]

1.3.3 Swap order flow

Banks may turn to the FX swap market in order to try to benefit from low funding costs in foreign currency, or try to exploit CIP arbitrage violations. From our high-frequency data from the Reuters D3000 platform (similar to the electronic limit order book for FX spot), we match transaction prices with bid and ask prices to infer if the initiator of the transaction was buying or selling USD at the spot leg. From this we create a daily measure of swap market order flow as the net of USD buyer-and

[19] Figure 1.7 below presents CP-OIS spreads for other currencies and longer samples. These figures show a significant compression in wholesale funding costs especially in EUR, CHF, and JPY when the central banks of the respective currency areas significantly expanded the supply of reserve balances as a by-product of their balance sheet policies.

[20] In the funding leg, it still remains important to consider interest rates that are not risk free. Otherwise, the relevant costs for the arbitrageur of engaging in the arbitrage are not adequately captured (see discussion in Section 1.2).

[21] In cases where the central bank has adopted tiered deposit remuneration (Bech and Malkhozov, 2016), we use the lowest rate as an expression of the marginal remuneration rate. The more favorable rates only apply to a restricted amount.

[22] For further discussion of cross-currency arbitrage based on OIS, see Online Appendix 1.C.

seller-initiated volume at the spot leg of the swap (For further details see Online Appendix B).[23] We are, to the best of our knowledge, the first paper to study the impact of order flow on intermediaries' FX swap market quotes.

1.4 Law of one price violations and CIP arbitrage

We now turn to our empirical study of LOOP violations and CIP arbitrage profits in international money markets. In line with the main focus of our work, our analysis relies on money market rates that are consistent with the marginal funding costs of the main arbitrageurs, i.e. globally active banks.

1.4.1 LOOP violations in international money markets

As discussed above, LOOP deviations give rise to opportunistic behavior, e.g. to either directly borrow in the target currency, or to fund in USD and swap into the target currency, depending on what is more attractive in terms of cost. Previous research shows that in the post-GFC world, the relevant arbitrage case has been to raise USD directly and swap into foreign currency (except for AUD. See Table 1.H.2 in the Online Appendix for all currencies). Thereby the arbitrageur is reaping the USD premium in the swap—arising from the USD being more expensive to borrow via the swap than directly in U.S. money markets. Hence, we will focus on this particular case in the following.

Figure 1.5 illustrates that the choice of interest rates is crucial when analyzing LOOP violations.[24] It shows box plots for the LOOP violations, over the post-crisis period (after 2013), averaged across the three currency pairs for which we have CP rates (EUR, JPY and GBP, against USD). We distinguish between four different money market rates: IBOR, interbank deposits, OIS and CP rates. For CP rates we look at the average across rating categories. For IBOR and OIS rates, i.e. interest rates that do not adequately capture marginal funding costs, we observe economically significant LOOP violations (vertical line inside bar) of around 15 basis points or higher on average over the post-crisis period. However, the main takeaway here is not that there are some LOOP deviations for certain interest rates (as also previous research has shown), but that LOOP violations are significantly lower for interbank deposits and basically non-existent for CP rates.[25] Most strikingly, in the case of CP rates, we observe median deviations of only around two basis points on average in the post-GFC period.

[Insert Figure 1.5 about here]

[23] Akram et al. (2008) analyzed high-frequency on pre-GFC data. In the post-GFC regime a daily frequency is sufficient. Analysis of high-frequency swap rates gives similar results and is available upon request.

[24] See Tables 1.H.4 – 1.H.5 and Figure 1.H.2 in the Online Appendix for other maturities and for separate currencies.

[25] A main reason why violations based on interbank deposits are so small, compared to IBOR rates, is that quotes of interbank deposits capture how banks are pricing funds internally, a common practice called Funds Transfer Pricing (FTP). This important institutional feature is discussed in Online Appendix 1.E.

The main reason is that CP rates—unlike some of the other money market rates—are better at capturing banks' marginal funding cost. An initial interpretation (further developed in Section 1.5 below) is that the price signals from CP markets serve as an important ingredient when swap dealers set FX swap quotes. In contrast to OIS rates which are commonly regarded as proxies for risk-free rates, CP rates additionally embed credit and liquidity premium components. Liquidity premia can differ notably across currency areas. An important factor is the liquidity regime in which the two central banks operate in, which in turn is determined by the relative supply of reserve balances to the system. That the CP-based LOOP violation is much smaller than the OIS-based deviation indicates that FX swap dealers draw on the former rates, embedding the currency-specific liquidity premia, when setting their quotes in the FX swap market (i.e. the so-called swap points).[26]

1.4.2 CIP arbitrage in international money markets

We now turn to our main analysis of CIP arbitrage in international money markets. For simplicity, our analysis in the following considers only arbitrage trades with direct borrowing in USD markets and swapping into foreign currency, as opposed to the other direction (given that the latter is not a profitable strategy. See e.g. Table 1.H.2 reported in the Online Appendix). Given the discussion above, we split the post-crisis sample into the period before and after the U.S. MMF reform. Although the MMF reform came into effect October 14, 2016, the major adjustments in funding markets occurred already several months as prime funds' assets under management dropped substantially (see Figures 1.3(b) and 1.4). Thus, we determine the start of the MMF reform period to be April 2016. This phase is a particularly interesting sub-sample and nicely illustrates changes in USD funding costs as the marginal buyers of bank-issued CP/CD scaled back their presence in unsecured funding markets.

Standard textbook treatments of CIP-arbitrage, e.g. Hull (2017), typically consider risk-free rates in both legs of the transaction. The reasoning is that the theoretically correct discount rate for a risk-free asset should be the risk-free rate. However, this argument rests on the ability to encumber the asset of interest to raise funding at the risk-free rate in the funding currency, e.g. as collateral in a repo. As discussed in Section 1.2.2, in a CIP-arbitrage trade the asset obtained in the investment leg is denominated in a currency other than that of the funding currency. This means that the trader cannot simply resort to the standard GC repo market in the funding currency, but has to conduct a special repo using the foreign currency denominated asset (say a Japanese or German T-Bill) as collateral to obtain the necessary USD funding. Doing so is significantly more expensive than GC repos, though, where the collateral is denominated in the same currency as the cash raised. Cross-currency collateral is more risky as it has different liquidity characteristics and is

[26] By contrast, LOOP violations based on (risk-free) OIS rates, that are insensitive to such premia, largely reflect fluctuations in the *relative* difference in funding liquidity premia across two currencies. Based on this interpretation, a widening of the OIS cross-currency basis is hence not necessarily an indication of arbitrage profits, but rather suggests that the costs of USD term funding (relative to other currencies) have gone up. See Online Appendix 1.F for a simple framework for identifying liquidity premium differentials, and how this measure varies with e.g. the OIS-basis.

difficult/costly to re-use if the cash lender faces sudden liquidity needs in the currency provided in the repo—again, a point that is most relevant for the USD given its special status in the financial system. To compensate, a dealer will therefore charge higher haircuts and/or higher interest rates for cross-currency collateral. Consequently, due to lack of available data on special repos, one way two overcome this issue is to employ the unsecured marginal cost in the funding leg.[27]

For the funding leg of the arbitrage, we therefore use CP rates as these provide us with realistic marginal funding costs for banks in the post-crisis market environment. As vehicles for the *risk-free* investment leg we consider (i) short-term government paper (T-bills), and (ii) central bank deposit facilities. Not only do these choices make sure that our analysis is in line with the basic requirements for arbitrage—namely that the arbitrageur is not exposed to risk while reflecting the relevant costs—but, the arbitrage strategies set up this way also bind little to no capital for banks.[28]

[Insert Table 1.3 about here]

Table 1.3 present results for 3-month CIP-arbitrage. Part I covers the first sub-sample, while results for the MMF reform sample are presented in Part II (also see Table 1.H.6 in the Online Appendix for other maturities). The left-hand panel shows CIP arbitrage profits with central bank deposit facilities as investment vehicle, while the right-hand panel of the Table reports profits when the funds are invested in T-bills. First, we consider USD funding costs by mid-rated (A-2/P-2) banks in the CP market, swapped into foreign currency and invested into the T-bill in the respective currency.[29] Panel A of Table 1.3 shows that during the first sub-sample hardly any arbitrage profits can be reaped for A-2/P-2 banks. For better-rated banks (Panel B), there are some arbitrage profits for investments in CHF- and JPY-denominated T-bills.

Table 1.3 (left-hand panel) reports CIP arbitrage profits when global banks borrow in USD CP markets and place the swapped funds in foreign central banks' deposit facilities. Panel A of the Table shows that in the CHF and the JPY some arbitrage profits have been available even for A-2/P-2 banks. These are fairly small in economic terms, though, around 1 and 4 basis points on average over the post-crisis sample period up to the U.S. MMF reform. For the set of high-rated global banks with good access to funding in USD markets (Panel B), the profits have generally been larger, with economically viable arbitrage opportunities as large as 14 basis points in JPY and CHF.

[27] This is especially relevant when using the central bank deposits as the investment vehicle as they do not give the trader any asset that could be pledged as collateral in the funding currency.

[28] The statement that a risk-free trade does not consume any capital may not be entirely correct in presence of Funding Value Adjustment (FVA), Credit Value Adjustment (CVA) and Leverage Ratio (Andersen et al., 2017; Duffie, 2018a). However, in this paper we are considering short-term trades (up to 3 months), which are much less affected by FVA and CVA. The FVA increases with the probability of default and loss given default. The shorter the maturity of the funding, the lower is the probability of default. Two-way Credit Support Annex (CSA) agreements, which are common among major market participants, significantly reduce both CVA and FVA in the FX swap. Only U.S. and U.K. banks have been subject to Leverage Ratio requirements during our sample period.

[29] Note that A-2/P-2 rated banks (while being rated some notches below high-rated banks in their CP issuance) can still be considered as fairly creditworthy institutions, relative to many other financial institutions that do not have access to the CP market in the first place.

It is noteworthy that arbitrage profits involving CB deposit facilities are much larger than when investing in T-bills. The difference in median profit between the two investment vehicles is between 5 and 20 basis points depending on currency and which rating category one is looking at. It is important to keep in mind that the rate of remuneration offered on central bank deposits is insensitive to the volumes placed in the facility. Moreover, there is segmentation in the sense that only a selected group of financial institutions has access to the deposit facility. On the other hand, the pricing of T-bills adjusts to demand and supply imbalances. If a cross-border arbitrage opportunity combining an FX swap and T-bills emerges, one would expect both the FX swap price and the T-bill rate to respond to the corresponding arbitrage induced flow.

Figure 1.6 illustrates the time series behavior of CIP profits involving either Treasury bills (Panel a) or central bank deposit facilities (Panel b) as investment vehicles. We average over EUR, CHF, and JPY in order to highlight the cases with positive CIP profits, as evident from Table 1.3 above, and use a two-week moving average to enhance the visibility of the key trends.[30] CIP profits funded by issuing CP are in all cases much smaller than what the cross-currency basis for OIS rates would suggest. For high-rated and mid-rated banks that invest in Treasury bills, there are only few periods with positive and economically attractive CIP arbitrage opportunities.

[Insert Figure 1.6 about here]

When central bank deposits are used as the investment leg, we see some prolonged periods with profitable CIP arbitrage opportunities in EUR, CHF, and JPY (Panel (b) in Figure 1.6). In particular, arbitrage profits pick up strongly in the run-up of the 2016 MMF reform—a major disruption to USD funding markets, as discussed above, when prime MMFs receded as main marginal lender in USD CP/CD markets due to shrinking assets under management. In this episode of widespread funding strains in USD markets, the median CIP arbitrage profits available to high-rated banks were as high as 30-40 basis points, as shown in Table 1.3 Part II. While this is economically attractive, it is however much lower than the 80-100 basis points suggested by the OIS-Basis. During this episode of strained USD funding conditions, even lower-tier banks have faced economically attractive arbitrage opportunities, with riskless profits as high as 26 basis points on average (in case of deposits with the Bank of Japan). Needless to say, however, that a pre-requisite for reaping such profits has been to be maintain access to wholesale non-bank USD funding markets in this challenging period, and for the bank to be eligible to the respective central bank deposit facility.

A natural reaction when presented with evidence of arbitrage is that some prices are measured incorrectly and some additional costs or risks are not taken care of. Given our careful choice of interest rates, one might ask if dealers for instance may embed a risk premium in their FX swap quotes to guard against counterparty risk. The source of FX swap prices, however, is the interdealer market where the use of two-way Credit Support Annex (CSA) agreements is common practice to govern

[30]Figure 1.H.3 in the Online Appendix shows that when averaging over AUD, CAD, and GBP, CIP seems to hold as profits are primarily negative.

the collateralization of the derivatives transaction. This means that both counterparties are obliged to pay variation margin according to price movements. This effectively eliminates counterparty risks and is the reason for negligible price differentiation in the interdealer market.[31] As a consequence, the FX swap prices used in this paper are the most appropriate to use for an arbitrageur.[32]

Interim summary. The empirical analysis above reveals the following preliminary lessons: (i) deviations from the law of one price are either non-existent, or an order of magnitude smaller when using marginal funding rates such as CP rates; (ii) for a large set of banks, either facing a lower rating or without access to the relevant central bank deposit facilities, economically attractive profits from CIP arbitrage are hard to reap due to elevated funding costs in USD markets. Even for high-rated banks, risk-less arbitrage profits tend to be lower than what common measures of the cross-currency basis suggest; (iii) during periods of funding strains in core USD funding markets CIP arbitrage opportunities have been sizeable for those institutions that retained market access. We now turn to a framework that can help us understand these empirical observations.

1.5 FX swap market equilibrium

The previous analysis begs a key question: How is it possible that risk-free arbitrage profits, even for a narrow set of banks, can persist over such an extended period of time? To tackle this question, it is important to study the problem faced by the key intermediaries, i.e. FX swap dealers.

Compared to the situation of no-arbitrage prior to the GFC, three major forces have altered the FX swap market equilibrium post-GFC: (i) greater heterogeneity in USD funding costs across banks; (ii) divergence in banks' funding liquidity premia in the USD vs. major currency areas (such as JPY and EUR), driven in large part by divergence in central bank balance sheet policies over the period (notably QE); (iii) limited scope for individual banks to scale the arbitrage, in particular due to quantity constraints affecting the price elasticity of the supply of USD.

These forces have created challenges for dealers that use their quote-setting behavior to extract intermediation spreads while obtaining a balanced book. We argue that the "new normal" in FX swap markets is characterized by an equilibrium where dealers face an incentive of quoting prices that imply arbitrage opportunities and that in turn are traded upon. However, such an equilibrium can only be sustained if arbitrage positions are not infinitely scalable. Hence, after discussing the equilibrium in the FX swap market under the post-crisis new normal, we turn to empirical evidence to shed light on the key mechanisms at play.

[31] While inter-dealer pricing is homogeneous, one can observe price differentiation in the dealer-to-customer segment, in particular depending on the way the trades are collateralized.

[32] Hau et al. (2017) show that the pricing of FX derivatives transactions is highly homogeneous for active, sophisticated, counterparties.

1.5.1 Divergence in funding liquidity premia

A notable development in money markets post-GFC is that funding liquidity premia have evolved differently across currency areas on the back of a divergence in central bank balance sheet policies and the associated supply of reserve balances. USD funding conditions tightened as the Fed balance sheet was no longer expanding from end 2014:Q2 onwards, whereas the size of balance sheets of central banks in the euro area, Japan, U.K. and Switzerland expanded strongly, going hand in hand with a commensurate increase in reserve balances. As Figure 1.7 shows, this has led to a situation where for a bank of a certain credit rating, it became much cheaper to raise funds in major currency areas outside of the U.S. (See also Figure 1.4 above and Figure 1.F.1 in the Online Appendix).

[Insert Figure 1.7 about here]

Such divergence in funding costs in turn has made it significantly more difficult for dealers to quote a price of the swap (the swap points implied by the F/S ratio) so that the law of one price holds for all money market rates at the same time. To see this, consider the following equation

$$\frac{F}{S} \approx \frac{1 + r^f_\$ + \widetilde{cr}_\$ + \widetilde{lp}_\$}{1 + r^f_\star + \widetilde{cr}_\star + \widetilde{lp}_\star}, \tag{1.3}$$

where $r^f_\$ + \widetilde{cr}_\$ + \widetilde{lp}_\$$ refer to the level of some USD interest rate (r^f represent the risk-free rate, $\widetilde{cr}$ the credit risk premium, and $\widetilde{lp}$ the funding liquidity premium). Prior to the GFC and central banks' reliance on unconventional policies, liquidity premia $\widetilde{lp}$ (for different currencies) were relatively small and roughly equal across currencies. If credit premia $\widetilde{cr}$ (for equally risky banks) were similar across currencies, the same F/S could ensure LOOP for different interest rates (or credit premia).

Figure 1.8 illustrates the importance of diverging liquidity premia for the FX swap market. Panel (a) illustrates how, in a normal market environment, a single swap rate can maintain the law of one price (LOOP) for different funding rates. The two vertical lines indicate interest rate levels in the two countries ("U.S." on the left-hand side and "Foreign" on the right-hand side). For simplicity, we look at three levels of funding rates faced by different banks in the credit spectrum (top, mid, low) as indicated on the vertical axis. The slope of the curve connecting interest rates in the two currency areas is the FX swap implied interest rate differential (as given by the F/S-ratio). If the vertical distance between the different interest rates is the same, e.g. when risk premia are aligned for equally risky banks, LOOP will hold for all levels of funding rates with just one F/S-ratio. The absence of any LOOP deviations is indicated by marking the curve with zeros.

[Insert Figure 1.8 about here]

Now consider the case of a divergence in liquidity premia across currency areas. A main reason behind such a divergence can be a large rise in the supply of reserve balances as a side-product of large-scale asset purchases or FX interventions, in turn leading to a compression in marginal funding costs of banks domiciled in the corresponding QE economies (see, e.g. Jondeau et al., 2020). In Figure 1.8 we assume that this leads to a drop as low as to the rate of remuneration of the central bank deposit facility. Banks at the bottom of the credit spectrum benefit disproportionately from the fall in short-term funding costs. An improvement in the ease of funding is akin to a fall in liquidity premia, $\widetilde{lp}_{\star}$ in Equation (1.3). As discussed above, a key feature of the post-crisis new normal in money markets has been that the relative funding liquidity premia have evolved differently across major currency areas: USD liquidity premia, $\widetilde{lp}_{\$}$, have typically been elevated, thanks in large part to structural demand for USD funding by non-U.S. domiciled global banks. By contrast, the costs of term funding dropped heavily in other currency areas where the respective central banks supplied ample liquidity to the banking system as a result of their balance sheet policies.

Panel (b) of Figure 1.8 illustrates the impact of a compression in banks' marginal funding costs in one currency area, while those in USD remain elevated. The previous bank-specific marginal funding costs in foreign currency, now in italics, are no longer binding in this situation. Instead, the rate of remuneration of the CB deposit facility has become the effective marginal funding rate for all banks (irrespective of credit-rating). The main reason is that banks awash with holdings of reserve balances, rather than obtaining market funding, can simply run down their holdings of excess reserves.[33] Hence, the rate of remuneration of reserves held at the foreign central bank's deposit facility determines funding costs at the margin. The Figure shows that in this situation it is impossible for an intermediary to quote a single FX swap rate to be consistent with LOOP (or CIP) for the key money market rates faced by all banks in the credit spectrum.

The difference in funding liquidity premia across currencies is partly due to the special role of USD in the global financial system as the world's primary invoicing, funding, investment and settlement currency (see e.g., Gopinath and Stein, 2018; Eren and Malamud, 2018). The USD money market is by far the largest and most vibrant in the world and globally oriented non-U.S. banks tap this market as the access to retail deposit funding in USD might be limited. However, these global banks have ample access to deposit funding (and potentially central bank funding) in their home currency (like EUR or JPY). Their enduring USD demand to finance USD assets can either be funded by directly raising USD in core U.S. money markets or by local currency funding swapped into USD. When the former type of funding becomes more difficult to obtain, it falls on the FX swap market to fill the gap.

[33] In the real world, there are limits to this behavior, however, for several reasons. Central bank reserve balances have become an important "asset" for banks to hold in the post-GFC money market landscape—in particular driven by liquidity regulation, stress testing and more prudent liquidity management practices. Given their superior liquidity characteristics, banks have revealed a preference of holding reserve balances over other liquid assets such as short-term Treasury securities. This also explain why—despite a significant amount of reserve balances held at the Federal Reserve—USD funding conditions tightened as the Federal Reserve started to gradually shrink its balance sheets since Q2:2014. As banks' demand for reserves has been more difficult to ascertain, determining the amount of reserve balances that can been deemed truly to be in "excess" has become very challenging.

1.5.2 Implications for dealers and order flow in the FX swap market

What does this imply for the main intermediaries in the FX swap markets, i.e. dealers? When a swap dealer enters into a transaction with a counterparty, she/he has three alternatives: (i) attract an opposite interest (matched book); (ii) fund the delivery of the currency as short as possible and invest the currency received until opposite interest is found, which involves taking on some (short-term) liquidity risk; (iii) fund the open position at the same maturity as the FX swap and invest at the same maturity. A dealer typically has a strong preference for the first option. This is further reinforced by internal overnight risk limits that effectively force the market-making desks to end the day "flat".

In the environment described above, any quote of FX swap points set by the dealer will imply a profitable opportunity for at least one set of swap end-users. Imagine a situation where the dealer quotes prices (i.e. swap points) such that the implied rate differential equals that between the USD rate faced by high-rated banks and the foreign central bank's deposit facility rate.[34] It is clear that such a quote cannot be an equilibrium rate because all banks with more costly direct funding in USD could obtain USD more cheaply via the swap-market. The dealer would face highly one-sided demand pressure for USD (indicated by arrows that point towards USD for the spot leg of the swap) and would accumulate a large inventory.

To be consistent with equilibrium, the quotes of the dealer thus need to induce flows in both directions. This is accomplished by setting the swap quote so as to imply an interest rate differential such that LOOP holds for the majority of banks that account for the bulk of USD demand.[35] Similarly as above (Panel (b)), banks with higher USD funding costs have an incentive to obtain USD via the swap market (i.e. a response to a LOOP deviation).

In this "new normal"-equilibrium the necessary flows in the opposite direction are induced by granting an arbitrage opportunity to those few banks with advantages in terms of USD funding costs. Their low USD funding rates render it attractive to borrow in unsecured USD markets, swap the dollars into foreign currencies and place the funds with foreign central banks (or other risk-free instruments, e.g. T-bills). The implied flows supporting this as an equilibrium are shown in Panel (d) of Figure 1.8 as arrows in both directions. The larger the divergence in liquidity premia, the steeper is the slope of the curves in Panel (d) of Figure 1.8, and the larger is the CIP-gain if one can invest in CB-deposits.

We argue that the main mechanism described above is also consistent with FX swap market developments around regulatory reporting dates. As Du et al. (2019) forcefully show, there are especially large basis-widenings around key regulatory reporting dates at quarter-ends and year-

[34] In Panel (b) of Figure 1.8, this case is indicated by the red dashed line connecting the foreign CB rate and the low U.S. rate, marked with zeros to indicate no deviation from LOOP for the high rated banks (and hence no CIP arbitrage).

[35] This is indicated by the solid red line marked by zeros in Panel (c) of Figure 1.8, connecting USD rates for mid-tier banks with the rate on the foreign central bank's deposit facility. Note that this quote implies a slightly steeper FX swap-implied rate differential than the non-optimal alternative ('dashed' line).

ends. A key reason is that banks practice so-called window-dressing behavior close to reporting dates aimed at fulfilling regulations tied to the size of the balance sheet. As we analyse empirically in the next section, FX swap market imbalances are especially acute in such periods. To keep a balanced book, dealers set FX swap quotes so as to incentivize arbitrage flow to offset strong demand for USD liquidity.[36]

1.5.3 Empirical evidence

We now investigate the predictions of the above framework empirically. First, we show that the pricing in FX swap markets responds significantly to swap order flow, suggesting that dealers revise their quotes to avert inventory imbalances. Second, we present evidence that highly rated banks, but not lower-rated ones, do in fact take advantage of the arbitrage opportunities. For this situation to be consistent with an equilibrium, such arbitrage opportunities must be bounded, though. As a third step, we present evidence of upward-sloping USD supply curves based on issuance data in the USD CD market, suggesting that potential arbitrageurs face limits to scaling up their positions.

FX swap market imbalances: the role of swap order flow. As outlined above, dealers have a primary incentive to quote FX swap points so that (in expectation) they face a balanced order flow from their counterparties. Imbalances can arise in a situation of severe constraints in USD funding markets, in particular when lower-tier banks face constraints to raise USD directly and need to turn to the swap market to fill the gap instead. Such imbalances will be associated with movements in swap order flow, i.e. flow into USD at the spot leg. Faced with such a situation, the swap dealer will have to quote a higher swap rate ($F - S$), thereby implying a steeper curve in Figure 1.8, in order to attract a matching flow of opposite sign. As outlined above, the opposing flow will come from less constrained banks in the USD market (typically highly rated banks), who are in a position to supply USD to the swap market. Consequently, our framework predicts that a CIP arbitrage opportunity (a positive CIP deviation) will arise for highly rated banks in response to a positive order flow imbalance.

To test this, we rely on panel regressions of the form

$$\Delta CIP^{dev}_{i,t} = \alpha_i + \gamma \cdot CIP^{dev}_{i,t-1} + D_{i,t} \cdot \beta_{swapOF} OF^{swap}_{i,t} + D_{i,t} \cdot \beta_x X_{i,t} + \varepsilon_{i,t}, \tag{1.4}$$

where we regress the change in CIP deviations for currency i on a measure of FX swaps order flow, $OF^{swap}_{i,t}$, and a set of control variables, $X_{i,t}$. Order flow is standardized and measured so that a positive number represents flow into USD at the spot leg and into foreign currency at the forward leg. The regression also includes the lagged level of CIP deviation to capture the forces pulling any deviations back to zero (akin to an error-correction mechanism). All variables capturing the dynamics are interacted with dummies $D_{i,t}$ indicating whether there is a deviation or not. This allows

[36] We discuss the role of regulations further in Online Appendix 1.G.

us to capture that the variables may have a different impact during periods of arbitrage opportunities than in more normal periods. As an extra control variable we use a broad spot FX USD index, as suggested by Avdjiev et al. (2019), where positive changes indicate a USD appreciation.[37]

[Insert Table 1.4 about here]

Table 1.4 presents regression results for 3-month arbitrage profits involving CB deposits as investment vehicles (given less scope for arbitrage using Treasury bills).[38] For each case, CIP arbitrage profits are computed based on CP funding costs by mid-tier (A-2/P-2) and highly rated banks (A-1/P-1). We find that the coefficient on swap order flow is positive and significant in all regressions, confirming the intuition of our framework. A positive coefficient on the order flow variable suggests that the demand pressure to obtain USD via swaps requires an increase in the CIP deviation.

The magnitudes of the estimated coefficients suggest that the price impact of order flow varies depending on how severe CIP deviations are. Interacting order flow with a CIP dummy shows that in orderly markets, with no deviation, only a small quote update of 0.17bp, for a one standard deviation change in flow, is needed to curb an order imbalance. During periods when deviations are observed for A-1/P-1 banks, a positive order flow imbalance signals to the swap dealer a worsening of funding conditions in U.S. money markets. In this case, the dealer may expect further demand pressure from lower-tier financial institutions to raise USD via the swap market. To cope with this, a large adjustment in the quoted FX swap points is necessary to attract offsetting arbitrage flow from highly rated banks. The price impact of 0.73 bp in Table 1.4, column (4) and (5), confirms this intuition. By the same token, a positive flow (into USD at spot leg) observed in a situation when also deviations for banks with lower ratings occur (A-2/P-2 in Table 1.4) serves as a signal of even worse funding conditions. This requires an even greater adjustment in swap quotes by the dealer to restore equilibrium, as indicated by the 1.1 bp price impact coefficient in column (1) and (2).

We also find notable differences in the price impact of swap order flow depending on whether it is the USD or the foreign currency that is sought after. Column (3) and (6) of Table 1.4 show the difference in price impact between flow into versus out of USD. Purely from a balance sheet perspective, it does not matter for the dealer which way the order flow is. If the dealer cannot match the order against opposite flow, she will have to finance the inventory position in the respective currency. Potential regulatory constraints should therefore transmit into the same price impact of order flow independently of the direction of the flow. In contrast, if funding constraints in USD markets are more severe than in other currencies—or in other words, when funding liquidity premia across currencies diverge—one would expect to see a larger coefficient for flows directed into USD (demand pressure to obtain USD), but less so for flows directed out of USD (demand pressure to obtain foreign currency). Our results clearly suggest that the latter mechanism is in play. The

[37] Alternative specifications, such as adding bilateral spot exchange rates, spot FX order flow, and our measure of liquidity premium differentials as control variables, are summarized in Figure 1.H.4.

[38] Table 1.H.7 in the Online Appendix shows results from fixed-effect panel regressions for all maturities and the Money Market Fund reform sample.

coefficients indicate a strong price impact of 1.2 bp and 0.7 bp when the order flow indicates a pressure to obtain USD. When the order flow indicates pressure to obtain foreign currency, we do not observe a significant impact and the coefficient estimate is much lower.

Our regressions indicate that order flow emerges as a more powerful variable to explain CIP arbitrage profits than the alternative variables we consider as controls. Estimated coefficients on the USD index are positive, but small and only barely statistically significant. Figure 1.9 summarizes the impact of swap market order flow, for different tenors, in periods of arbitrage. In all three cases (1-week, 1-month and 3-month), the price impact of order flow is positive and significant. The impact of order flow is higher for CIP profits by mid-tier banks, and it is also higher for shorter maturities.

[Insert Figure 1.9 about here]

The impact of flow imbalances is especially powerful around regulatory reporting dates. As mentioned in the previous section (and further elaborated in Online Appendix 1.G), the costs involved with carrying balance sheet over the end-of-quarter indeed generate fairly extreme outcomes in the FX swap market (see also Du et al., 2019). In Table 1.5 we study 1-month and 1-week maturities, the maturities most affected, and interact the price impact of swap order flow with an End-of-Quarter dummy. Impact is about twice as large during the End-of-Quarter period (1 week (month) before for 1-week (-month) maturity) compared to other periods. These large price impact estimates reflect the strong incentives for banks to swap liquidity-abundant currencies into USD around these periods, while at the same time the supply of USD will be fairly inelastic. Faced by this demand/supply constellation, swap dealers need to adjust their quotes of FX swap points even more to elicit opposing arbitrage flow by top-rated banks.

[Insert Table 1.5 about here]

CIP arbitrage and central bank deposits. We now provide some evidence on the footprint of global banks' CIP arbitrage involving central bank deposit facilities. Our previous results showed that the Japanese yen stands out as the currency with the most attractive CIP arbitrage opportunities, in particular when considering the central bank deposit facility in the investment leg (Table 1.3). One would therefore expect the pricing in FX swaps and the CIP arbitrage profits available by investing at the Bank of Japan's deposit facility to have indeed attracted arbitrage capital.

Figure 1.10 shows JPY cash holdings by foreign banks operating in Japan (green bars), as well as the amounts placed in the deposit facility of the central bank (red bars). Panel (a) shows JPY holdings by highly rated banks, while those of all other global banks active in Japan are depicted in Panel (b). Blue bars represent the amount of net headquarter funding from abroad.

[Insert Figure 1.10 about here]

As can be gleaned from the graph, highly rated banks have indeed bolstered their JPY cash holdings with the Bank of Japan substantially in recent years, primarily by channeling funds from their head office and effectively exploiting CIP arbitrage opportunities. Responding to the incentives given the pricing in international money markets, yen holdings by high-rated foreign banks have picked up especially since the introduction of the QQE (Quantitative and Qualitative Easing) program by the Bank of Japan in April 2013. In Panel (a) we superimpose the annual average CIP deviation that supports this interpretation. Figure 1.10, Panel (b), also suggests that globally active banks that do not enjoy a top rating have increased their holdings at the Bank of Japan much less, in contrast to their better-rated peers. This evidence is consistent with the prediction of the framework above that banks with access to cheap funding in USD exploit the cross-currency arbitrage trade.

Limits to arbitrage scalability. Our previous results suggest that to arbitrage CIP deviations, the burden falls on a confined set of highly rated banks to supply a significant amount of USD in the FX swap market. What is preventing these banks from deploying even more capital to the arbitrage? To study this question we turn to an analysis of certificate of deposit (CD) issuance in USD markets. Descriptive statistics on issuance volumes are presented in Table 1.6.[39]

[Insert Table 1.6 about here]

Drawing on the CD transactions of individual banks' with access to this funding market, Figure 1.11 depicts the corresponding profits from CIP arbitrage trades. A first takeaway is the large heterogeneity in funding costs across banks: Even within the set of highly rated banks that do have access to USD CD markets, there are quite a few that do not enjoy economically attractive arbitrage opportunities given their elevated funding costs.[40]

[Insert Figure 1.11 about here]

To shed light on the scalability of CIP arbitrage, we study the relationship between USD funding spreads (CD minus the OIS rate) and volume using individual CD transactions. Our goal is to test whether the price of USD funding picks up as banks seek to place higher issuance volumes. To test this, we rely on panel regressions of the form

$$r^{CD}_{i,t,m} - r^{OIS}_{t,m} = \beta_1 \cdot CDvolume_{i,t,m} + \lambda_{i,t} + \alpha_{t,m} + \varepsilon_{i,t,m} \tag{1.5}$$

where $r^{CD}_{i,t,m} - r^{OIS}_{t,m}$ is the CD-OIS spread for bank i at time t with maturity m, $CDvolume_{i,t,m}$ is the issued volume, $\lambda_{i,t}$ is bank-time fixed effects and $\alpha_{t,m}$ is maturity-time fixed effects. The standard errors are clustered at the bank level.

[39] In our regression analysis below, we exclude issuances below USD 1 million to make sure that very small issuances, in particular those issued by small U.S. banks, do not contaminate our results.

[40] Also note that CIP arbitrage profits appear slightly lower when we consider volume-weighted averages of CD rates compared with baseline results using CP rates that do not take volume information into account (see Figure 1.H.5 in Online Appendix).

[Insert Table 1.7 about here]

By including bank-day fixed effects and maturity-day fixed effects, we can control for economically important unobservable effects. Important unobserved time-varying bank characteristics that may affect the banks' funding costs can, for instance, be the perceived risk on different banks' balance sheets. It also deals with the issue that longer-maturity funding spreads tend to increase more when funding liquidity conditions tighten (i.e. the term structure of funding spread steepens). Finally, we report the result for each of the maturities separately to ensure that maturity effects are not driving our results.

Table 1.7 reports the results. We find that a USD 100 million increase in CD issuance volume corresponds to a 1 basis point increase in funding costs.[41] This means that for a given bank, at a given date and for a given maturity, controlling for time-varying bank and maturity characteristics, funding costs increase significantly by volume issued. This in turn suggests limited scalability of the arbitrage trades. Turning to the maturity-specific estimates, our results indicate that the volume effect is largest at the 3-month maturity. A USD 100 million increase in CD issuance volume corresponds to a 2.68 basis point increase in funding costs. Results are quantitatively similar when the sample is restricted to high-rated banks only.

One important reason why the USD supply curve is likely to be upward-sloping is that the marginal investors in unsecured short-term bank liabilities, i.e. U.S. money market funds, care about concentration risk and do not consider banks with different risk profiles to be perfect substitutes for each other. For instance, if a high-rated bank increases issuance of short-term debt, typical investors may not be able to meet this demand due to limits on the concentration risk posed by large investments in specific issuers, even when the bank issuing the debt is of high quality.

1.6 Conclusion

The absence of arbitrage is the most fundamental mechanism in financial markets. Common measures suggest that CIP, a no-arbitrage condition once considered to be a cornerstone of international financial markets, is broken. We argue that to understand the CIP conundrum, a new perspective is warranted. In the post-crisis environment, characterised by fragmented USD funding markets and a substantial heterogeneity in funding costs (both across banks and across currency areas), it is no longer possible for the law of one price to hold for the full spectrum of interest rates simultaneously. Careful attention needs to be paid to select the interest rates capturing the marginal funding costs at which banks can borrow to set up the arbitrage position.

The main message from our paper is that the law of one price in fact holds remarkably well for the majority of market participants when considering money market rates that reflect banks' marginal funding costs. That said, we find that economically attractive CIP arbitrage opportunities

[41] Table 1.6 shows that USD 100 million is below the average amount of a CD primary market issuance. This Table also shows that the largest issuances have exceeded USD 4 billion.

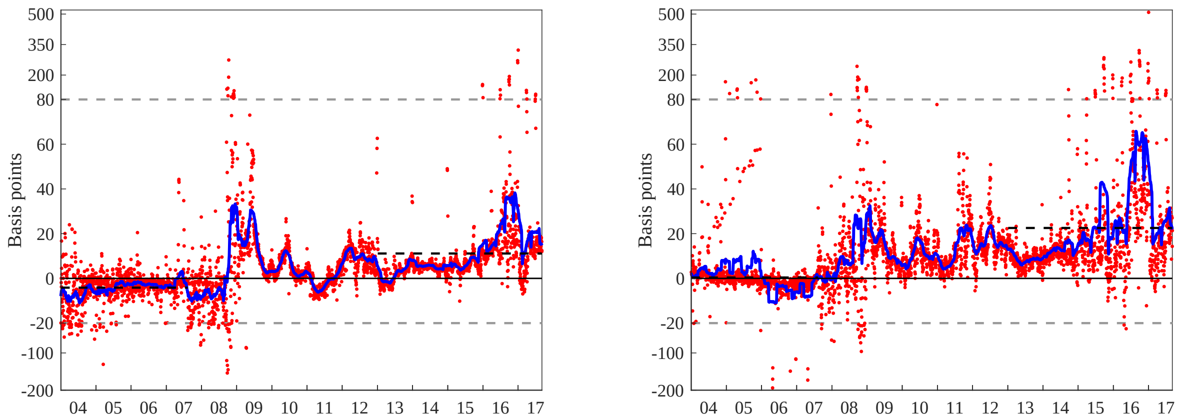
do exist—but, they are confined to a few high-rated global banks. The key reason why CIP arbitrage for these banks is profitable is favourable access to USD Commercial Paper (CP) and Certificates of Deposit (CD) markets where banks can raise funding from non-bank institutional investors at the lowest cost. Moreover, the fact that these banks operate globally gives them access to safe investment vehicles in foreign currency, particularly central bank deposit facilities.

This raises the fundamental question of how a situation with riskless arbitrage profits, even if only for a confined set of banks, can persist over a prolonged period of time. We show how such arbitrage opportunities emerge as an equilibrium outcome as FX swap dealers set prices to avoid inventory imbalances. Mid-rated banks find it attractive to turn to the FX swap market to cover their USD funding, while swap dealers elicit opposite (arbitrage) flows by high-rated banks. The price impact of FX swap order flow is particularly strong—and arbitrage profits greatest for high-rated banks—when lower-tier banks have an incentive to turn to the FX swap market to obtain USD funding.

Such arbitrage opportunities for a few high-rated banks can persist as the arbitrage positions are difficult to scale. Drawing on issuance data for USD CDs, we show that funding rates adjust as soon as arbitrageurs increase their positions, in turn significantly reducing profits. All in all, the evidence presented in this paper suggests that the main paradigm of CIP—i.e. the non-existence of riskless arbitrage profits after accounting for the risk and relevant costs incurred by the arbitrageur—still remains largely valid in post-crisis financial markets, at least for the majority of market participants.

Tables and Figures

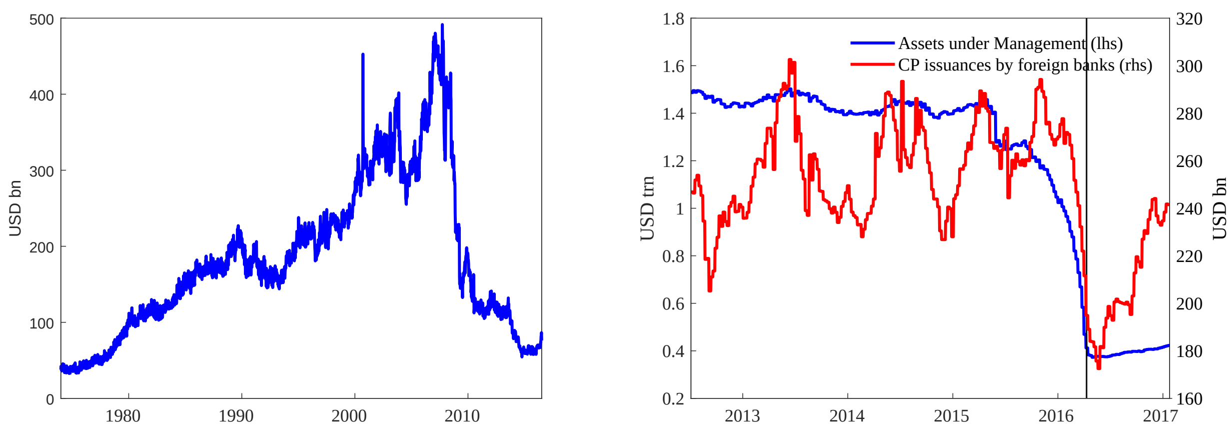
Figure 1.1
IBOR-basis for GBP and JPY (1-week)



(a) GBPUSD (b) USDJPY

Notes: The Figure shows the 1-week IBOR basis for Sterling (GBP) and the Japanese yen (JPY) vis-a-vis the U.S. dollar (USD). Individual observations of the IBOR-basis are shown in red dots, while the blue solid lines depict a smoothed series for ease of visibility (based on a 3-month moving average). The units are in basis points. Positive values indicate a higher synthetic dollar rate (implied via the FX swap market) when compared to the direct USD rate, or in other words, that foreign currency LIBOR swapped to USD is higher than USD LIBOR. Black dotted lines represent the average basis in the periods up to and after the Global Financial Crisis. The gray dotted lines on the vertical axis indicated points where the axis is broken in order to ease presentation of extreme values. Sample is January 2004 — August 2017. Source: Bloomberg.

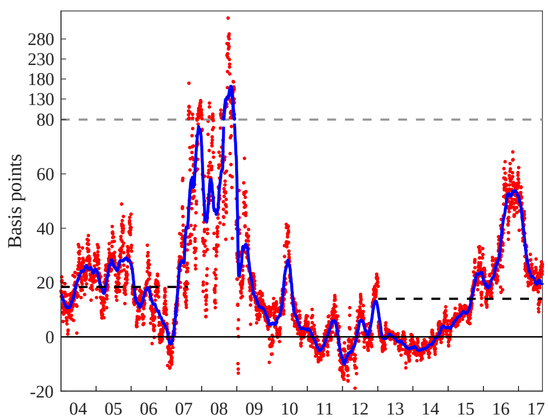
Figure 1.2
Activity in U.S. money markets



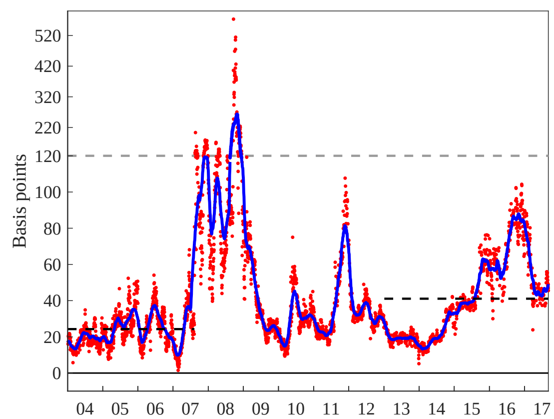
(a) Activity in U.S. interbank markets (b) U.S. prime money market funds

Notes: The Figure shows activity and major developments in U.S. money markets. Panel (a) shows the evolution of weekly aggregate volumes in U.S. interbank markets. The sample period is from January 1975 until June 2017 and represents interbank loans issued by all commercial banks. The original source is the H.8 Assets and Liabilities of Commercial Banks in the United States released by the Board of Governors of the Federal Reserve System. The left-hand axis of Panel (b) shows the evolution of the assets under management of prime U.S. money market funds in USD trillion. The right-hand axis shows the volumes issued by foreign financial institutions in the U.S. commercial paper market (in USD billion). The vertical line marks the introduction of the U.S. Money Market Reform on October 14, 2016, and the sample is January 2013 — June 2017. Source: St. Louis FRED database.

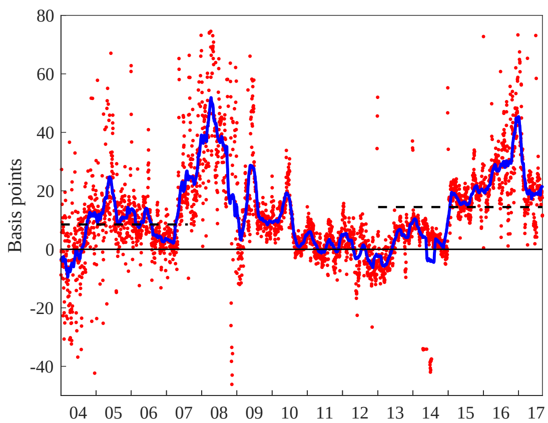
Figure 1.3
Basis based on T-bills (3-month) and repos (1-week) for GBP and JPY



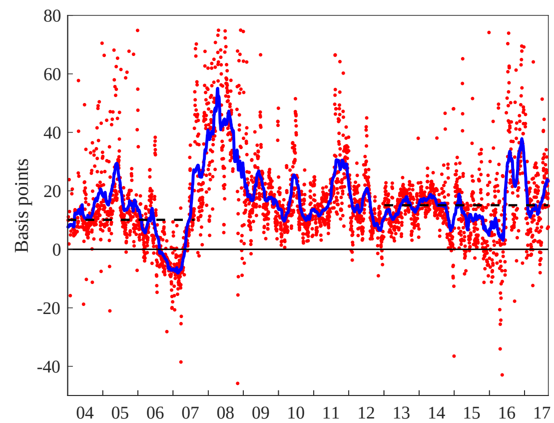
(a) 3m Tbill-basis, GBPUSD



(b) 3m Tbill-basis, USDJPY



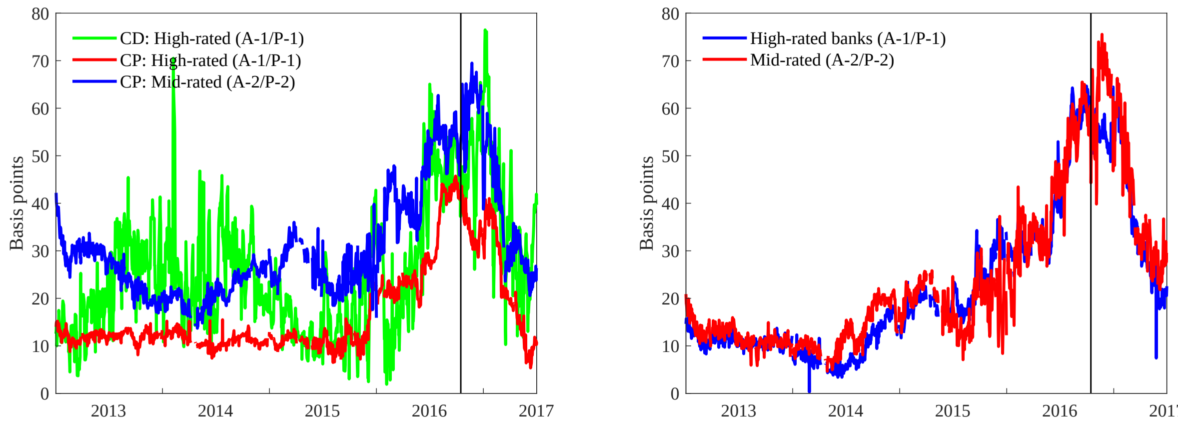
(c) 1w repo-basis, GBPUSD



(d) 1w repo-basis, USDJPY

Notes: The Figure shows the evolution of the 3-month T-Bill basis and the 1-week repo basis for Sterling (GBP) and the Japanese yen (JPY) vis-a-vis the U.S. dollar (USD). Individual observations of the respective bases are shown in red dots, while the blue solid lines depict a smoothed series for ease of visibility (based on a 3-month moving average). The units are in basis points. Positive values indicate a higher synthetic dollar rate (implied via the FX swap market) when compared to the direct USD rate. Black dotted lines represent the average basis in the periods up to and after the Global Financial Crisis. The gray dotted lines on the vertical axis indicated points where the axis is broken in order to ease presentation of extreme values. Sample is January 2004 — August 2017. Source: Bloomberg and Global Financial Data.

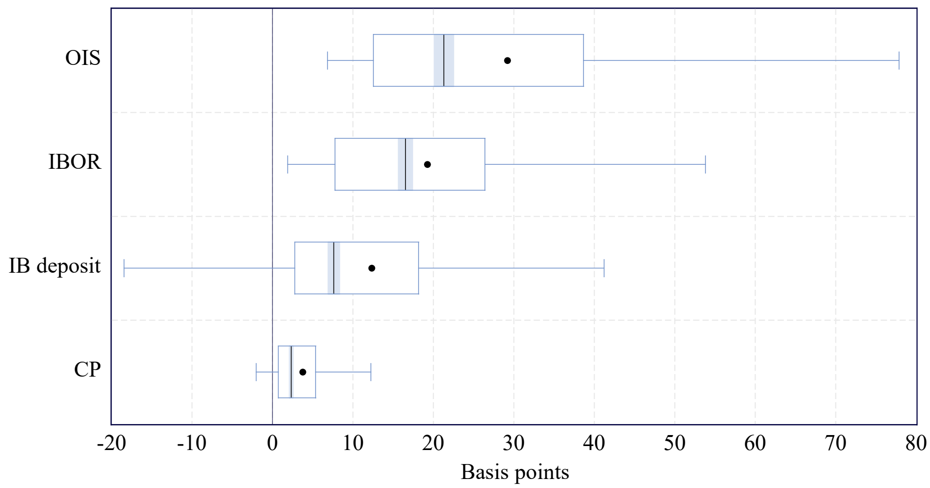
Figure 1.4
U.S. dollar unsecured funding spreads (3-month)



(a) CP-OIS and CD-OIS spreads (b) USD CP-OIS minus average foreign CP-OIS spread

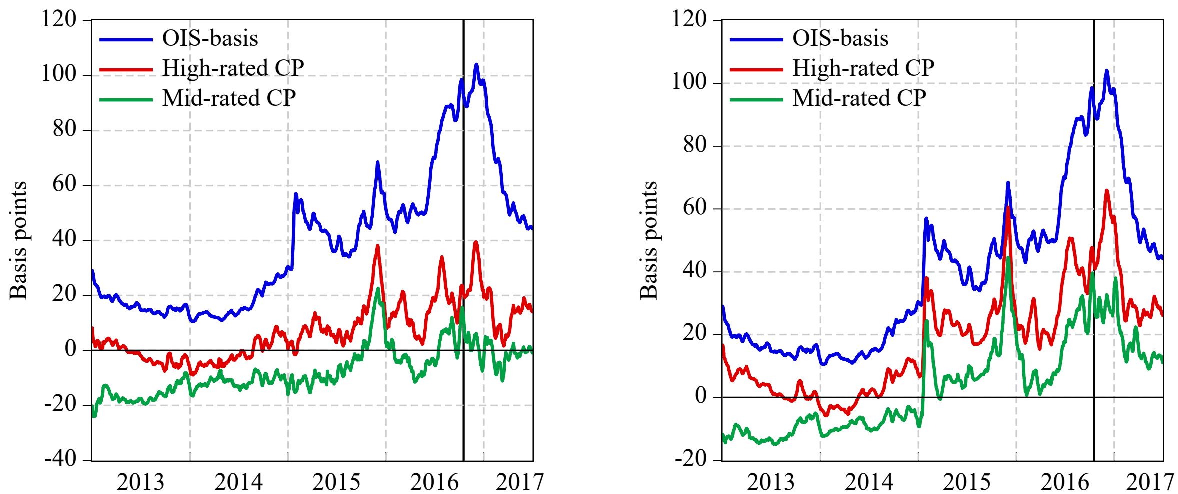
Notes: The Figure depicts the evolution of 3-month unsecured funding spreads in USD in the post-GFC period, as well as a comparison to the same spreads in major foreign currencies. Panel (a) shows spreads of USD Commercial Paper (CP) over OIS rates for high-rated (A-1/P-1 rating) and mid-rated (A-2/P-2) banks, together with moving average (10 days) of volume-weighted Certificate of Deposit (CD) rates, over OIS, from issuances by high-rated banks. The units are in basis points. Panel (b) compares the funding spreads in USD markets for a given rating category, to the same spreads in other major currencies; it shows the difference between USD CP-OIS spreads and that of EUR, GBP and JPY (averaged across the three currencies) for high-rated (A-1/P-1) and mid-rated (A-2/P-2) banks. The vertical line indicates October 14, 2016, the date of the implementation of the U.S. Money Market Fund reform. Sample: January 2013 — June 2017.

Figure 1.5
LOOP deviations for different money market rates (3-month maturity)



Notes: The Figure shows box plots displaying law of one price (LOOP) deviations, measured in basis points, for different 3-month money market rates. Positive values indicate a higher synthetic dollar rate (implied via the FX swap market) when compared to the direct USD rate. For ease of exposition, the average across the currencies for which we have CP-rates (EUR, JPY and GBP) is shown and LOOP deviations for CP rates are averaged across rating categories. Elements of the box plot are as follows: the box itself represents the first and third quartile; inside the box, the mean is represented by a dot, while the median by a line; the shaded area around the median represents the 95% confidence interval; the staples (end of straight line) represent the value of the last data point within 1.5 from either the first or the third quartile. Sample: January 2013 – June 2017.

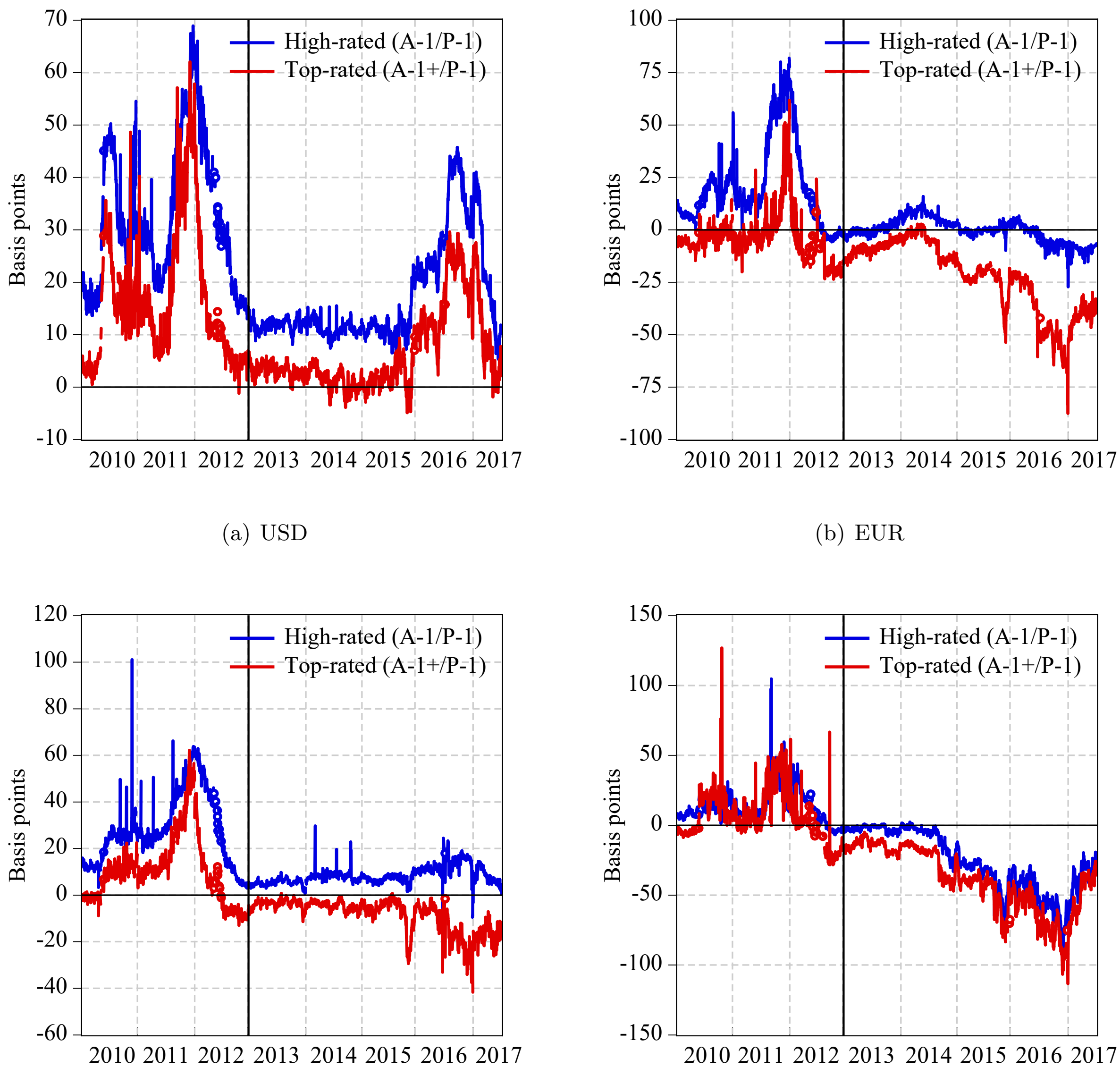
Figure 1.6
Risk-free 3-month CIP arbitrage opportunities for global banks compared to OIS basis



(a) Invest in T-bills (b) Invest in CB deposits

Notes: The Figure shows risk-free CIP arbitrage profits—averaged over EUR, CHF and JPY—for global banks when funded via the issuance of USD commercial paper, swapping into foreign currency and placing the funds in foreign Treasury bills (panel a) or the foreign central banks' deposit facility (panel b). Funding rates differ for mid-rated banks (A-2/P-2) and high-rated banks (A-1/P-1). In both panels we also show the 3-month OIS basis for comparative purposes. All series are smoothed with a 2-week moving average. The vertical lines indicate October 14, 2016, the date of the implementation of the U.S. Money Market Fund reform. Sample: January 2013 – June 2017.

Figure 1.7
CP-OIS spreads (3-month maturity)

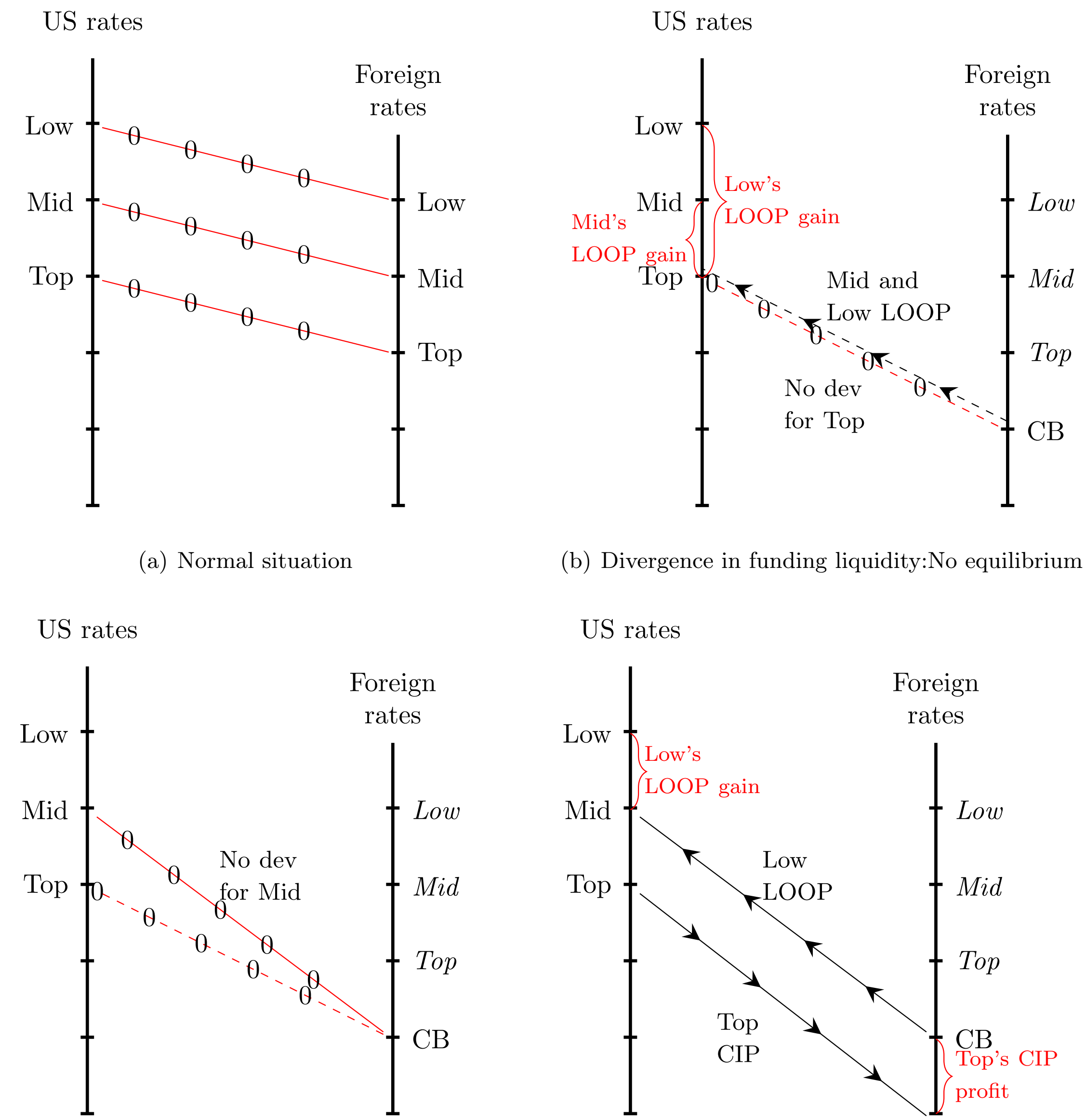


(a) USD (b) EUR

(c) GBP (d) JPY

Notes: The Figure depicts the evolution of the spread between the 3-month Commercial Paper (CP) rate over the 3-month OIS rate for two rating groups and four currencies. Rating A-1/P-1, which is used throughout the paper, is compared to the even better rating A-1+/P-1. The sample runs from 2010 to June 2017. The vertical line at January 2013 indicate the end of the period with the GFC and euro-crisis, and the beginning of the sample for our main analysis.

Figure 1.8
FX swap market equilibrium



(a) Normal situation

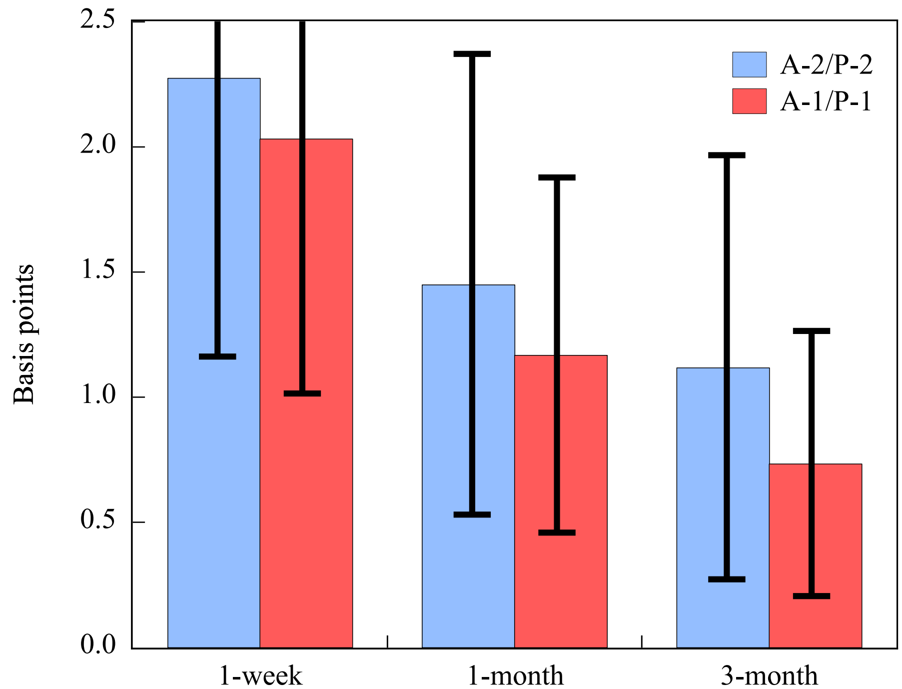
(b) Divergence in funding liquidity:No equilibrium

(c) Divergence in funding liquidity: Equilibrium swap rate

(d) Divergence in funding liquidity: Equilibrium swap flows

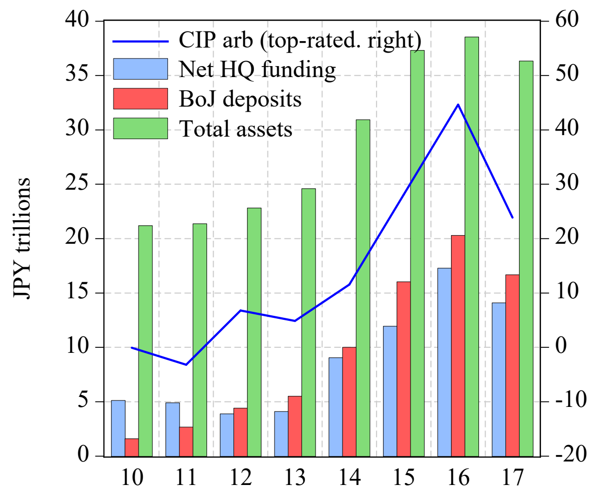
Notes: The Figure characterizes FX swap market equilibrium, by illustrating the link between various types of interest rate differentials, swap rates and the direction of swap flows. The two vertical lines indicate the interest rate levels in the two countries, exemplified by the "U.S." (left) and "Foreign" (right). The curve connecting the two interest rates is the FX swap-implied interest rate differential (in short, the "swap rate"). Since all market participants face the same swap rate, these swap rate curves are shifted vertically. A red line marked with zeros means that there are no LOOP deviations (Panel a). The solid lines represent market rates, whereas the dashed line represents a hypothetical rate. The black line suggest a profitable opportunity, and the arrows show the direction of swap flows in the "spot leg" of the swap (Panels b-c). Arrows from U.S. rates mean a profitable opportunity by directly raising dollars in U.S. funding markets. In Panel (d), the arrows from U.S. indicate a CIP deviation because the risk-free investment rate is higher than the implied borrowing rate. The arrow to the U.S., however, indicates a LOOP deviation as there are no risk-free U.S. investment opportunities available at higher rates than the swap-implied rate.

Figure 1.9
Relation between swap order flow and CIP arbitrage profits across maturities

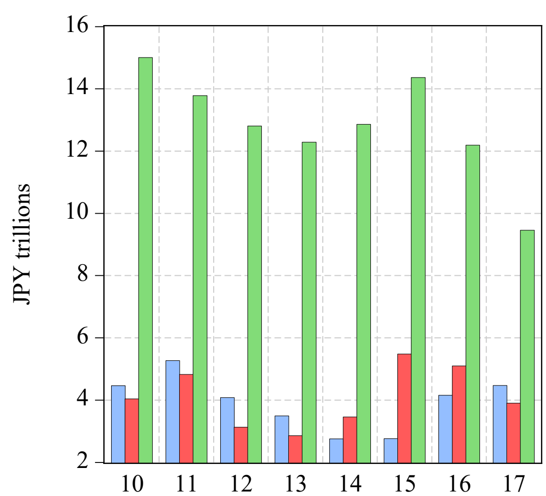


Notes: The Figure shows the impact coefficient, in basis points, of (standardized) swap order flow on CIP arbitrage profits (funding in U.S. CP-rates and investing in CB deposits), conditioned on being in a positive arbitrage state. Results are shown for three different maturities. Vertical lines indicate $\pm$ 2 $\times$ coefficient standard errors, which are symmetric but truncated at the top if they reach outside the graph area. Regression results are based on regressions similar to column (1) and (3) in Table 1.4. Coefficients measure the impact of a one standard deviation change in swap order flow. See Figure 1.H.4 in the Online Appendix for other regression specifications. Sample for estimation: January 2013 – June 2017.

Figure 1.10
Foreign banks' cash deposits with Bank of Japan



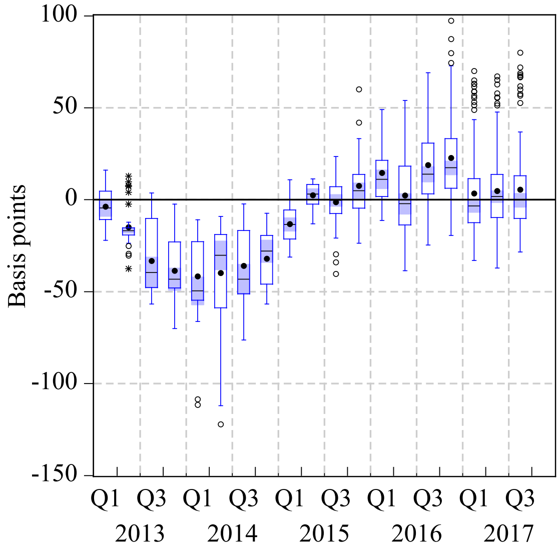
(a) High-rated banks (A-1/P-1)



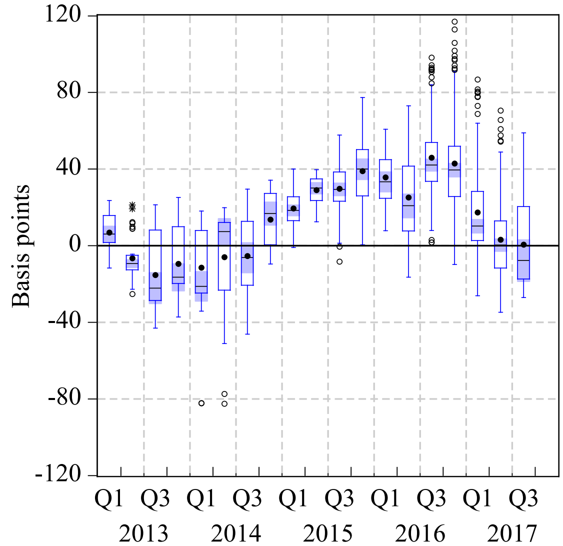
(b) Mid-rated banks (A-2/P-2)

Notes: The Figure shows the assets, measured in trillions of JPY, of global banks' subsidiaries in Japan, for different rating categories. Green bars show total assets, red bars are holdings of cash (held at the Bank of Japan deposit facility), and blue bars show net funding by headquarters. High-rated banks (Panel a) are rated A-1/P-1 (and include some with A-1+/P-1 rating), while Panel (b) is for all other banks. In Panel (a) we superimpose the average CIP arbitrage profit recorded in June each year in basis points (on right axis) from funding in CP rates and deposting the funds in the Bank of Japan's deposit facility. Source: KPMG Japan.

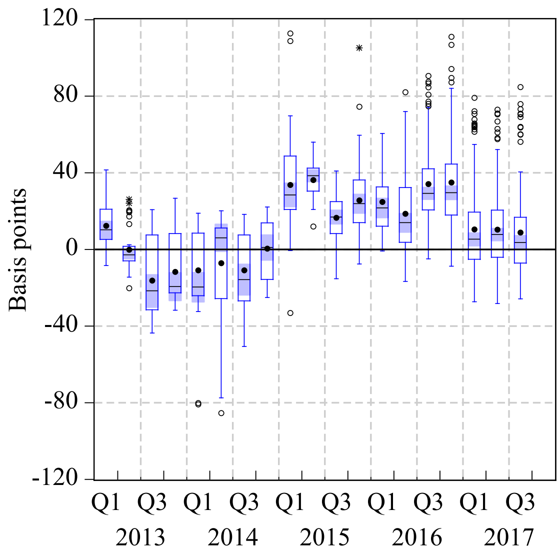
Figure 1.11
Dispersion in CIP arbitrage opportunities (funded via CD issuance) across high-rated banks (3-month maturity)



(a) EUR



(b) JPY



(c) CHF

Notes: The Figure shows the dispersion in CIP arbitrage opportunities, when invested in central bank deposits, across high-rated (A-1/P-1) banks given their heterogeneity in funding costs in USD CD markets. Positive numbers indicate positive arbitrage profits. The dispersion is captured by quarterly box plots. The box shows the first and third quartile of the data, together with the mean (dot) and median (line). The vertical lines measure the distance to points within a range (1.5) outside the inter quartile range, while the dots outside are defined as outliers. Panels (a-c) show CIP arbitrage opportunities when swapping to EUR, JPY and CHF, respectively.

Table 1.1
Comparison of money market spreads for different currencies (3-month maturity)

	Mean	Median	Std. Dev.	Obs.
		A: Commercial paper		
		Mid-rated banks (A-2/P-2)		
EUR	10.71	13.10	7.63	1,105
GBP	18.76	18.80	5.03	1,099
JPY	-8.50	-7.12	15.32	1,054
USD	31.41	27.80	12.13	1,099
		High-rated banks (A-1/P-1)		
EUR	-0.22	0.10	5.68	1,104
GBP	8.51	8.01	3.84	1,101
JPY	-25.73	-26.96	21.83	1,098
USD	17.00	12.37	9.39	1,099
		B: IBOR interbank rates		
AUD	20.97	20.90	8.21	1,171
CAD	31.94	28.08	6.46	1,130
CHF	-11.36	-12.62	10.74	1,137
EUR	9.31	10.00	4.19	1,150
GBP	11.16	10.24	3.80	1,136
JPY	4.97	5.40	2.71	1,137
USD	18.45	14.56	8.22	1,137
		C: Interbank deposit rates		
AUD	49.26	50.00	18.27	1,173
CAD	30.44	25.40	14.33	1,174
CHF	-1.78	2.85	16.19	1,174
EUR	12.73	12.90	5.43	1,172
GBP	28.05	28.00	11.47	1,173
JPY	3.34	6.20	10.98	1,174
USD	31.48	29.50	14.06	1,173

Notes: The Table presents descriptive statistics for spreads between different 3-month money market rates and OIS rates across currencies. Panel A presents results for Commercial Paper (CP) for high-rated (A-1/P-1) and mid-rated (A-2/P-2) banks, Panel B presents for IBOR rates, while Panel C for interbank deposits. All rates are measured as ask rates, and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017. See the Online Appendix Table 1.H.1 for 1-week and 1-month tenors.

Table 1.2
Descriptive statistics: Risk-free investment vehicles in CIP arbitrage (2013-June 2017)

A. T-bills

	Mean	Median	Stdev	Obs
AUD	25.97	14.55	92.13	339
CAD	-4.94	-5.20	4.87	1,146
CHF	-2.35	2.45	16.11	1,125
EUR	-10.81	-6.55	11.51	1,165
GBP	1.47	1.12	5.86	1,016
JPY	-7.58	-5.29	9.13	755
USD	-10.81	-10.31	4.72	1,173

B. Central bank deposits

	Median	Ave.change	#change	June 2017
AUD	2.25	-0.25	6	1.50
CAD	0.75	-0.25	2	0.50
CHF	0.75	—	0	0.50
EUR	-0.20	-0.10	4	-0.40
GBP	0.50	-0.25	1	0.25
JPY	0.10	-0.20	1	-0.10
USD	0.25	0.25	4	1.25

Notes: The Table presents summary statistics for risk-free investment vehicles in risk-free CIP arbitrage. Panel A presents descriptive statistics on the difference between 3-month T-bill rates and OIS rates, ie. $i^{TB} - i^{OIS}$. Panel B provides summary statistics on the remuneration on central bank deposit facilities. All T-bill rates are measured as ask (offer) rates. The German T-bill rate is used for EUR. The SNB (CHF) and BoJ (JPY) have a tiering structure for their deposit rates, meaning that not all reserves are remunerated at the same rate. Sample: January 2013 - June 2017.

Table 1.3
Risk-free CIP arbitrage funded via the CP market (3-month maturity)

	Investment rate: Central bank deposit facilities					Investment rate: Treasury bills				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
I: Post-crisis to beginning MMF reform period (Jan 2013 – Mar 2016)										
A. Mid-rated banks (A-2/P-2)										
AUD	**-54.8**	11.5	0	0	701	**-47.7**	81.8	0	0	222
CAD	**-20.2**	7.0	0	0	783	**-29.5**	7.0	0	0	758
CHF	**1.4**	16.4	56	33	783	**-12.8**	11.2	14	4	762
EUR	**-22.0**	11.9	7	1	780	**-15.7**	6.6	5	0	723
GBP	**-14.1**	5.4	1	0	782	**-32.0**	7.7	0	0	745
JPY	**4.6**	14.8	68	55	781	**-4.9**	11.4	32	13	537
B. High-rated banks (A-1/P-1)										
AUD	**-43.8**	11.4	0	0	701	**-34.5**	80.8	0	0	222
CAD	**-7.7**	5.4	14	2	783	**-16.1**	5.3	1	0	758
CHF	**14.2**	17.4	100	97	783	**0.6**	11.4	53	15	762
EUR	**-6.8**	13.5	34	26	780	**-1.4**	7.5	42	19	723
GBP	**-0.3**	3.6	47	25	782	**-18.7**	7.4	2	0	745
JPY	**14.2**	14.7	100	100	781	**6.0**	11.7	90	77	537

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving unsecured borrowing in the U.S. money market. The sample covers the post-crisis period and prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). Two risk-free choices for the investment leg are considered: central bank deposit facilities (left-hand panel) and T-bills (right-hand panel). Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits and the proportion of days (%D) and months (%M), as 20 consecutive days, during the sample when a positive arbitrage profit is observed.

Table 1.3
(Continued) Risk-free CIP arbitrage funded via the CP market (3-month maturity)

	Investment rate: Central bank deposit facilities					Investment rate: T-bills				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
	II. MMF reform sample (Apr 2016 – June 2017)									
	A. Mid-rated banks (A-2/P-2)									
AUD	**-67.6**	8.9	0	0	294	**-50.1**	9.2	0	0	111
CAD	**-29.5**	6.2	0	0	316	**-30.5**	7.9	0	0	316
CHF	**19.6**	10.5	99	84	316	**7.9**	8.6	85	44	310
EUR	**10.2**	9.4	83	75	316	**-11.9**	8.1	3	0	316
GBP	**-7.1**	7.2	13	0	315	**-24.5**	8.5	0	0	211
JPY	**26.4**	14.1	100	100	307	**8.4**	11.5	78	37	182
	B. High-rated banks (A-1/P-1)									
AUD	**-52.3**	5.9	0	0	294	**-33.6**	8.0	0	0	111
CAD	**-13.3**	6.5	4	0	316	**-13.8**	7.5	3	0	316
CHF	**34.8**	13.2	100	100	316	**23.4**	11.0	100	98	310
EUR	**25.5**	11.4	100	100	316	**4.4**	8.2	71	27	316
GBP	**8.8**	8.9	85	52	315	**-7.4**	8.0	17	0	211
JPY	**42.9**	16.3	100	100	307	**26.4**	14.4	97	88	182

Notes: The Table shows CIP arbitrage profits, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the transition phase of the U.S. money market fund reform from April 2016 – Dec 2016. Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). Two risk-free choices for the investment leg are considered: central bank deposit facilities (left-hand panel) and T-bills (right-hand panel). Columns give the average CIP arbitrage profit, the standard deviation of CIP arbitrage profits and the proportion of days (%D) and months (%M), as 20 consecutive days, during the sample when a positive arbitrage profit is observed.

Table 1.4
CIP arbitrage and FX swap market order flow imbalances

	Mid-rated (A-2/P-2)			High-rated (A-1/P-1)		
	(1)	(2)	(3)	(4)	(5)	(6)
Error correction	-0.035	-0.035	-0.036	-0.020	-0.020	-0.020
	(-3.23)	(-2.99)	(-4.70)	(-2.12)	(-1.97)	(-2.52)
Swap OF, in arb.	1.116	1.138		0.733	0.743	
	(2.64)	(2.61)		(2.77)	(2.75)	
Pos. Swap OF, in arb.			1.215			0.714
			(3.59)			(3.55)
Neg. Swap OF, in arb.			1.019			0.782
			(0.94)			(1.25)
Swap OF, no arb.	0.172	0.182	0.181	0.192	0.215	0.215
	(3.95)	(4.10)	(4.09)	(5.03)	(5.45)	(5.44)
Dollar index, in arb.		0.008	0.008		0.014	0.014
		(1.43)	(1.42)		(3.10)	(3.07)
Dollar index, no arb.		0.005	0.005		0.004	0.004
		(1.50)	(1.50)		(1.95)	(1.94)
Lagged ΔCIP	-0.186	-0.203	-0.204	-0.107	-0.127	-0.127
	(-3.51)	(-4.16)	(-4.25)	(-1.50)	(-2.01)	(-2.11)
Obs.	5,969	5,569	5,569	5,969	5,569	5,569
adj.R^2	0.08	0.10	0.10	0.06	0.08	0.08

Notes: The Table shows results from panel regressions of changes in 3-month CIP deviations on FX swap order flow, across six different currencies. CIP deviations are based on an arbitrage strategy funded in the U.S. Commercial Paper market for either mid-rated (A-2/P-2) or high-rated (A-1/P-1) banks and measured in basis points. The constant (not reported) and error-correction term (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on dummy variable capturing whether a profitable CIP arbitrage (arb) exists or not. Swap order flow is standardized by its standard deviation, while the broad dollar index return is measured in basis points. Columns (3) and (6) add a dummy variable to the specification depending on whether order flow is positive (into USD at spot leg) or not. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: January 2013 – June 2017.

Table 1.5
CIP arbitrage, FX swap order flow market imbalances, and End-of-Quarter effects

			1-month		1-week	
			A-2/P-2	A-1/P-1	A-2/P-2	A-1/P-1
			(1)	(2)	(3)	(4)
Error correction			-0.046	-0.028	-0.198	-0.146
			(-2.58)	(-2.28)	(-3.73)	(-2.26)
Swap OF						
	In arb	EoQ	1.771	1.998	7.839	9.831
			(4.15)	(4.65)	(3.53)	(4.07)
	In arb	Not EoQ	1.010	0.907	3.771	2.897
			(4.26)	(6.40)	(3.96)	(3.53)
	No arb	EoQ	1.318	1.100	8.200	2.111
			(1.28)	(2.46)	(11.25)	(5.35)
	No arb	Not EoQ	0.284	0.169	0.724	0.847
			(1.28)	(2.62)	(2.34)	(2.07)
Dollar index						
	In arb	EoQ	0.078	0.071	0.389	0.461
			(2.92)	(3.13)	(6.89)	(2.78)
	In arb	Not EoQ	-0.018	0.002	-0.002	0.011
			(-1.33)	(0.26)	(-0.07)	(0.38)
	No arb	EoQ	0.010	0.004	-0.022	0.015
			(0.64)	(0.37)	(-0.35)	(0.15)
	No arb	Not EoQ	-0.024	-0.006	0.003	0.009
			(-2.01)	(-0.68)	(0.25)	(0.62)
Lagged ΔCIP			-0.207	-0.061	0.018	0.044
			(-4.46)	(-1.36)	(0.25)	(0.56)
Obs.			1,648	1,648	1,631	1,408
Adj.R^2			0.13	0.10	0.12	0.11

Notes: The Table shows results from panel regressions of changes in CIP deviations (1-month and 1-week maturity) on FX swap order flow, across six different currencies, for the MMF reform period. CIP deviations are based on an arbitrage strategy funded in the U.S. Commercial Paper market for banks with either A-2/P-2 rating or high-rated banks with A-1/P-1-rating and measured in basis points. The constant (not reported) and error-correction terms (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on dummy variables capturing whether a profitable CIP arbitrage exists or not (arb), or if it is in an End-of-Quarter (EoQ) period. End-of-quarter effects start 1-week (1-month) before for a 1-week (1-month) tenor. Swap order flow is standardized by its standard deviation, while the broad dollar index return is measured in basis points. Positive order flow implies a buying pressure of USD at the spot leg of the swap. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: April 2016 – June 2017.

Table 1.6
Descriptive statistics on issuance volume of USD Certificates of Deposit (mio USD)

	Total	Mean	Std.Dev.	Max	Obs
Aggregate (average)	84,179	134	172	1,268	1,215
Small countries (average)	6,704	77	85	354	209
Canada	388,332	268	306	1,930	1,449
Japan	343,026	153	188	2,730	2,242
USA	291,785	20	67	1,400	14,887
China	250,944	40	59	600	6,353
Hong Kong	211,500	100	168	1,700	2,115
Switzerland	187,590	390	522	4,550	481
Sweden	155,805	255	277	1,600	611
France	91,875	175	199	3,200	525
Netherlands	77,724	306	355	1,960	254
United Kingdom	72,800	182	232	1,610	400
Germany	68,392	332	565	4,640	206
Australia	32,500	250	426	3,000	130

Notes: The Table presents summary statistics for issuance volume of Certificates of Deposit (CD) in USD. The first row presents aggregate numbers across all countries, while the 10 countries with the largest total issuances are presented in the following rows. Sample: January 2013 – June 2017.

Table 1.7
Impact of CD issuances on USD funding costs

	All banks				High-rated banks			
	Maturity							
	All	All	3-month	6-month	All	All	3-month	6-month
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Amount Issued	1.05	0.85	2.68	0.75	0.91	0.86	3.40	0.69
	(2.98)	(2.11)	(1.96)	(2.42)	(2.89)	(2.42)	(2.15)	(2.01)
Fixed effects:								
Bank × day	X		X	X	X		X	X
Maturity × day	X	X			X	X		
Bank × month		X				X		
Obs	8,283	15,449	2,623	3,203	3,581	8,015	1,190	1,340

Notes: The Table presents panel regressions for the impact of CD issuance volume on the CD-OIS spread. Maturities included are 1-month, 3-month and 6-month. All issuances considered are larger than USD 1mio. Coefficients measure impact in basis points for a 100 mio USD issue. t-values, based on standard errors clustered at the bank level, in parenthesis, singleton observations removed iteratively. Sample: January 2013 – June 2017.

Table 1.8
Data sources and description

	Source	Code example	Tenors	Currencies	Comment
		A. Unsecured money market rates			
Commercial Paper (CP)	TradeWeb/TR Eikon	YUSD3MCP=TWEB	1M, 3M	USD, EUR, GBP, JPY	Rating: A-1+/P-1; A-1/P-1; A-2/P-2
Certificate of Deposit (CD)	Bloomberg	Extensive ISIN-search	1W-6M	USD	Trades
Interbank Deposit	TR TickHistory	USD3MD=,BID	1W-3M	All (USD, AUD, CAD, CHF, EUR, GBP, JPY)	High Freq
	TR Eikon	USD3MD=,BID	1W-3M	All	
IBOR	Bloomberg	US0003M INDEX	1W-3M	All (AUD^1)	
		B. Risk-free interest rates			
Central bank deposits	Bloomberg	EECBDEPO INDEX		All	Example: ECB
Treasury bills	Bloomberg	USGG3M INDEX BID	3M	All	
Overnight Indexed Swaps (OIS)	TR TickHistory	GBP3MOIS=,ASK	1W-3M	All (AUD^2, CAD^2, CHF^2, GBP^2, JPY^2)	High freq
		C. FX instruments			
Spot FX	TR TickHistory	EUR=D2,ASK		AUD^3, CAD, CHF, EUR^3, GBP^3, JPY, against USD	Trades, High freq
	Bloomberg	EURUSD CURNCY ASK		All	
Dollar index	St.Louis Fed FRED	DTWEXB		Broad index	
FX Swaps	TR TickHistory	EUR3M=,BID	1W-3M	All	High freq
	Bloomberg	EUR3M CURNCY BID			
FX Swaps (D3)	TR TickHistory	EUR3M=D3,BID	1W-3W	All	Trades, High freq
		D. Other data			
Days to maturity	TR Eikon	Built-in function			
Interbank activity	St.Louis Fed FRED	IBLACBW027NBOG			
Assets under management	St.Louis Fed FRED	WMMFAMNA			
CP issuances by foreigners	St.Louis Fed FRED	FCPOFFS			
Foreign banks holding of JPY deposits	KPMG Foreign banks in Japan Survey	Several reports			

Notes: The Table gives an overview of data sources and instruments considered. The maximum range of tenors we have is 1-week (1W, or SW, Spot week), 2-week (2W), 3-week (3W), 1-month (1M), 2-month (2M), and 3-month (3M), with focus on 3-month horizon in text and 1-week and 1-month in appendix. The maximum available set of currencies includes the Australian dollar (AUD), the Canadian dollar (CAD), the Swiss franc (CHF), the euro (EUR), the pound sterling (GBP), and the Japansese yen (JPY). "TR" in the source-column is short for "Thomson Reuters." "D2" and "D3" in the code-example means sourced from Reuters D2000-2 and D3000-3, electronic limit order books for trading in FX markets. Superscript notes: 1: Not all tenors available for AUD. 2: For AUD, CAD and CHF, shortest tenor available is 1 month. 3: These currencies are base-currency vis-a-vis the USD, otherwise USD is base.

Appendix

Supplementary Internet Appendix to accompany

Covered Interest Parity Arbitrage (Not for publication)

List of Online Figures:

List of Online Tables:

1.A Equations for LOOP and CIP calculations

Covered Interest Parity (CIP) is typically, in a simplified way, expressed as

$$1 + r_d = \frac{1}{S}\left(1 + r_f\right)F, \tag{1.6}$$

where r_d and r_f are domestic and foreign interest rates, respectively, and S and F are spot and forward rates, expressed in units of domestic currency for a foreign currency, and the forward contract has the same maturity as the interest rates. This equation is obviously a simplification since it disregards that prices come with a bid-ask spread, ie. differ if one borrows (ask-rates) or lends (bid-rates), or buys (ask) or sells (bid) currency.

CIP is typically thought of as an arbitrage, i.e a self-financing round-trip. We can also use it to compare two borrowing (or lending) rates, in which case we are studying the Law of One Price (LOOP) as discussed in Section 1.4. Furthermore, one has to consider whether one takes the perspective of domestic borrowing, in which case one buys spot and sells forward, or vice versa in the case of foreign borrowing. LOOP is a weaker condition than CIP (Akram et al., 2009).

1.A.1 CIP: Round-trip arbitrage

Taking bid-ask prices into account, represented by b and a superscripts, respectively, CIP is *not* violated if the following conditions hold:

$$(1 + r_d^a) \geqslant \frac{F^b}{S^a}(1 + r_f^b), \tag{1.7}$$

$$(1 + r_f^a) \geqslant \frac{S^b}{F^a}(1 + r_d^b). \tag{1.8}$$

Using swap rates instead of forward rates, represented by $\overline{F^b - S^a}$ and $\overline{F^a - S^b}$ for bid and ask swap rates, respectively, then a positive arbitrage Dev is given by,

$$Dev^b \quad > \quad 0 \Rightarrow \overline{F^b - S^a} > S^a \frac{r_d^a - r_f^b}{1 + r_f^b}, \tag{1.9}$$

$$Dev^a \quad > \quad 0 \Rightarrow \overline{F^a - S^b} < S^b \frac{r_d^b - r_f^a}{1 + r_f^a}, \tag{1.10}$$

where the arbitrage superscript comes from the superscript on the forward leg of the swap (i.e, Dev^a in the case of USDJPY means buying USD at the forward leg).[42]

We can rewrite this as a condition between actual and swap-based interest rates, the so-called

[42] Rewrite the no-arbitrage CIP condition as the forward rate, $\frac{(1+r_d^a)}{(1+r_f^b)}S^a \geqslant F^b$, and subtract S^a from both sides to get the condition above.

cross-currency basis. On the bid-side:

$$
\begin{aligned}
\overline{F^b - S^a}\frac{1+r_f^b}{S^a} &> r_d^a - r_f^b \\
\overline{F^b - S^a}\frac{1+r_f^b}{S^a} + 1 + r_f^b - 1 &> r_d^a \\
\frac{\overline{F^b - S^a}}{S^a}\left(1+r_f^b\right) + \frac{S^a}{S^a}\left(1+r_f^b\right) - 1 &> r_d^a \\
\left[\frac{S^a + \overline{F^b - S^a}}{S^a}\right]\left(1+r_f^b\right) - 1 &> r_d^a \qquad (1.11)
\end{aligned}
$$

Proceeding similarly for the ask-side gives the following two conditions for measuring profitable CIP deviation using cross-currency basis representation:

$$
Dev^a \quad > \quad 0 \Rightarrow \left[\frac{S^b + \overline{F^a - S^b}}{S^b}\right]\left(1+r_f^a\right) - 1 < r_d^b, \qquad (1.12)
$$

$$
Dev^b \quad > \quad 0 \Rightarrow \left[\frac{S^a + \overline{F^b - S^a}}{S^a}\right]\left(1+r_f^b\right) - 1 > r_d^a \qquad (1.13)
$$

1.A.2 LOOP: One-way arbitrage

The law of one price can be violated either for borrowing rates (ask) or lending rates (bid). Strictu senso, this is not an arbitrage as it is only relevant for those that have a borrowing or lending need at the outset. As discussed in Section 1.4, responding to LOOP can be compared to exploiting relative value opportunities, but does not require expanding the balance sheet.

If we take the perspective of borrowing rates, these are *not* in violation if the following holds:

$$
\begin{aligned}
Ask &: \quad 1 + r_d^a \leq \frac{1}{S^b}\left(1+r_f^a\right)F^a \\
Bid &: \quad 1 + r_f^a \leq S^a\left(1+r_d^a\right)\frac{1}{F^b}
\end{aligned}
$$

The first condition says that it is cheaper to finance in the domestic market than to shop around to borrow abroad and swap into domestic currency. The second equation states the same, but from the perspective of the foreign market.

Expressed with swaps, these conditions become:

$$
\begin{aligned}
Ask : \frac{r_d^a - r_f^a}{1 + r_f^a}S^b &\leq \overline{F^a - S^b} \\
Bid : \overline{F^b - S^a} &\leq S^a\frac{r_d^a - r_f^a}{1 + r_f^a} \qquad (1.14)
\end{aligned}
$$

These equations can be rearranged to express the condition as difference between actual and swap-implied interest rates, i.e. the basis. At the ask-side,

$$
\begin{aligned}
\frac{r_d^a - r_f^a}{1 + r_f^a} S^b &\leq \overline{F^a - S^b} \\
r_d^a &\leq \frac{1 + r_f^a}{S^b} \overline{F^a - S^b} + r_f^a \\
r_d^a &\leq \left[\frac{S^b + \overline{F^a - S^b}}{S^b} \right] \left(1 + r_f^a\right) - 1 \\
r_f^a &< \left(1 + r_d^b\right) \frac{S^b}{S^b + \overline{\overline{F^a - S^b}}} - 1.
\end{aligned} \tag{1.15}
$$

For the bid side:

$$
r_d^a < \left[\left(\frac{S^a + \overline{F^b - S^a}}{S^a} \right) \left(1 + r_f^b\right) - 1 \right] \tag{1.16}
$$

1.A.3 Adding market conventions

There are several issues that have to be taken into account when such conditions as stated above are used in calculations based on actual market data. We list them here:

1. Swaps are not priced as forward price minus spot price, but rather in the units of the smallest decimal of the spot price (so-called pips). For example, if $F = 1.1001$ and $S = 1.000$, then the quoted swap is 1 (and not 0.0001). So quoted swap prices must be divided by 10 to the power of the number of decimal points. For most currencies this is 4, while for JPY it is 2.

2. Interest rates are quoted in percentage points and not as a share of 100 as above. All the 1s in the above equations must therefore be replaced by 100.

3. Interest rates are quoted as annual rates, and not for the maturity time-horizon. Hence, the interest rates must be corrected for this by multiplying by number of days to maturity divided by number of days in a year, $D/YEAR$. Most countries calculate with 365 days in a year, except the UK which uses 360. Days to maturity must respect that both markets are open, and the interested reader is referred to Akram et al. (2008) for details. Bloomberg and other financial services can provide the exact days for any date and currency pair.

When applied to the CIP basis at the bid, the condition then becomes:

$$
Basis_{CIP}^b = -r_d^a + \left[\left(\frac{S^a + \overline{F^b - S^a}/10^4}{S^a} \right) \left(100 + r_f^b \frac{D}{360}\right) - 100 \right] \frac{360}{D}. \tag{1.17}
$$

1.B Construction of high-frequency data

We primarily use high-frequency data for the creation of daily time series for FX swap order flow and spot order flow. Results based on high-frequency intraday analysis of CIP deviations when funded in interbank deposits (focus of previous drafts) are available upon request, but are omitted here as interbank deposits are no longer a vibrant source of funding.

We follow Akram et al. (2008) closely and collect high-frequency data for interbank deposits rates, OIS rates, FX spot and FX swaps, as shown in the overview in Table 1.8. All high-frequency data are timed to the thousandth of a second (millisecond) and are from 2005 until June 2017. We merge all data to the exact time and fill in with previous prices if an instrument does not have an updated quote in a particular millisecond.

Spot exchange rates are taken from the Reuters D2000-2 Electronic Limit Order Book, one of the primary wholesale trading platforms for trading FX Spot. The D2000-2 is an inter-dealer platform, which is mostly used by market makers to offload inventory positions from trades with end-users. This market thus performs an important risk-sharing function.

We use FX swaps instead of forwards because this is how sophisticated participants in interbank markets implement forward transactions. For FX swaps, we rely on two different sources, indicative quotes and data from the FX swap part of the electronic limit order book Reuters D2000-2 (this part is often labelled D3000-3).

We create measures of order flow for spot and FX swaps based on transactions on the electronic limit order books. By matching transaction prices with the prevailing best bid and ask quotes, we can determine the sign of the trade, positive (1) for buyer-initiated trades (at ask) and negative (-1) for seller-initiated trades. For FX swaps we construct the order flow to measure the net number of buyer/seller-initiated trades in USD in the spot leg of the swaps. Hence it serves as a proxy of demand and supply imbalances in the swap market, available at high frequency. Daily aggregates are created based on weekdays between GMT 01:00-18:00 and only for active trading days.

In some part of our analysis we rely on interbank deposit rates. The deposit quote on the ask side is an indication of the rate at which the quoting bank is willing to lend funds to another bank (i.e. placing deposits). The bid-quote is an indicative price for borrowing funds (i.e. accepting deposits) from another bank. Both bid and ask rates are quoted continuously throughout the day. OIS is a derivative, but the quote on the ask-side can be interpreted as the borrowing rate.

1.C CIP arbitrage with OIS contracts

This section provides some details on CIP arbitrage involving Overnight Indexed Swap (OIS) contracts. As discussed in the main text, OIS contracts are derivatives and no vehicles that could easily be used for funding purposes. Thus, OIS rates do not capture marginal funding costs of the key arbitrageurs. Yet, they are still very useful to provide a reference, in particular as the cross-currency basis based on OIS rates can be regarded as a reflection of the relative term liquidity premium in USD vs other currencies.

In this section, we note that relying on OIS contracts in CIP arbitrage exposes the arbitrageur to rollover risks. This can be a further impediment to arbitrage activity.

Implementing a CIP arbitrage trade based on OIS contracts is fairly complicated (illustrated by Figure 1.C.1). We repeat the sequence of trades here for convenience:

1. Borrow funds overnight (O/N) in the borrowing currency,
2. Roll over the O/N loan daily over the preferred maturity and hedge the interest rate risk by paying the (fixed) OIS rate of the same maturity,
3. Buy the lending currency spot, hedging the exchange rate risk by selling the lending currency forward at the date when the OIS matures,
4. Invest the lending currency O/N,
5. Roll over the O/N investment and hedge the interest rate risk by receiving the OIS rate in the lending currency.

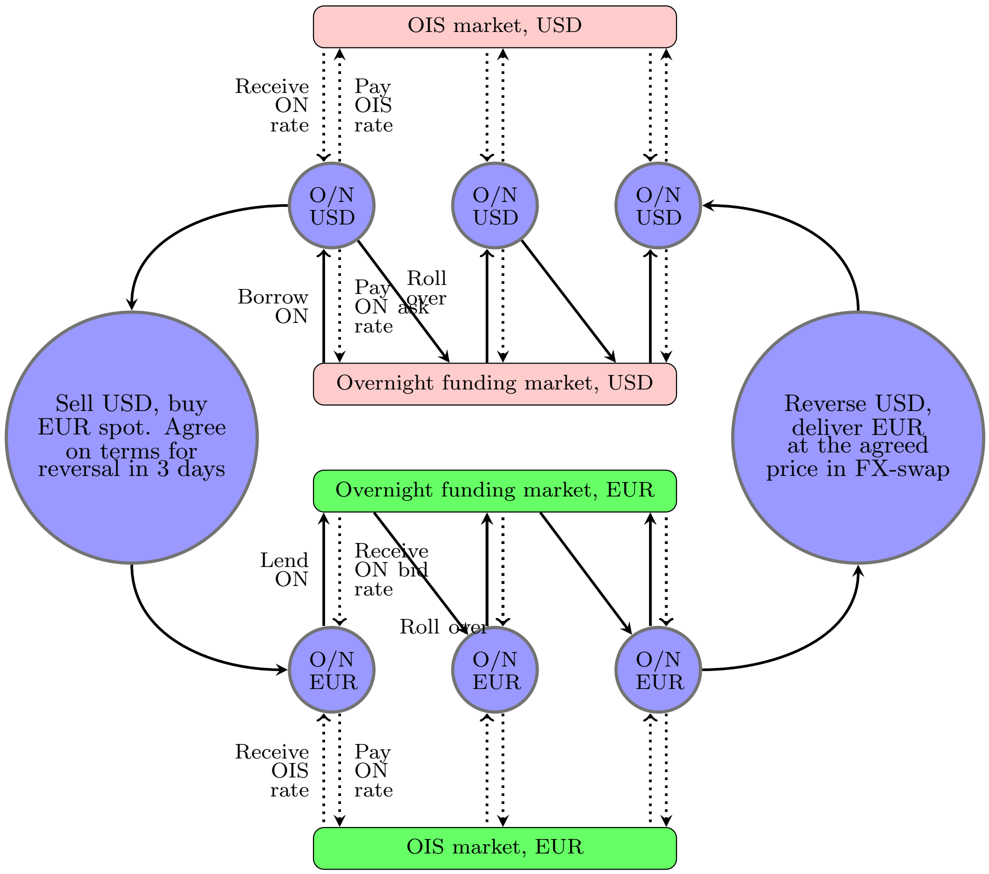
The issue of rollover risk is best illustrated by looking at the difference between quoted O/N interbank deposit rates and the underlying O/N rate in the OIS contract for EUR and USD.[43] If an arbitrageur seeks to exploit a widening of the OIS-basis, she has to constantly borrow USD in the U.S. O/N market and place EUR-denominated funds in the EUR area O/N market. This may have to be done at different rates than the weighted average of the money market transactions that are used for the fixing of the underlying O/N rate in the OIS contract.[44]

It is well-known, for instance, that the effective Federal funds rate that constitutes the underlying overnight interest rate in USD OIS contracts, is heavily affected by transactions involving Government-sponsored Entities (Fannie Mae, Freddie Mac and 11 Federal Home Loan Banks). These institutions can transact in the Fed funds market, but do not have access to the Fed's deposit facility (Bech and Klee, 2011). The Fed funds market may deviate from the O/N eurodollar market, a

[43] The underlying O/N rates in the EUR and USD OIS contracts are EONIA and the effective Fed funds rate, respectively.

[44] Griffoli and Ranaldo (2010) also point this out, but assume in the remainder of their analysis that this spread is negligible.

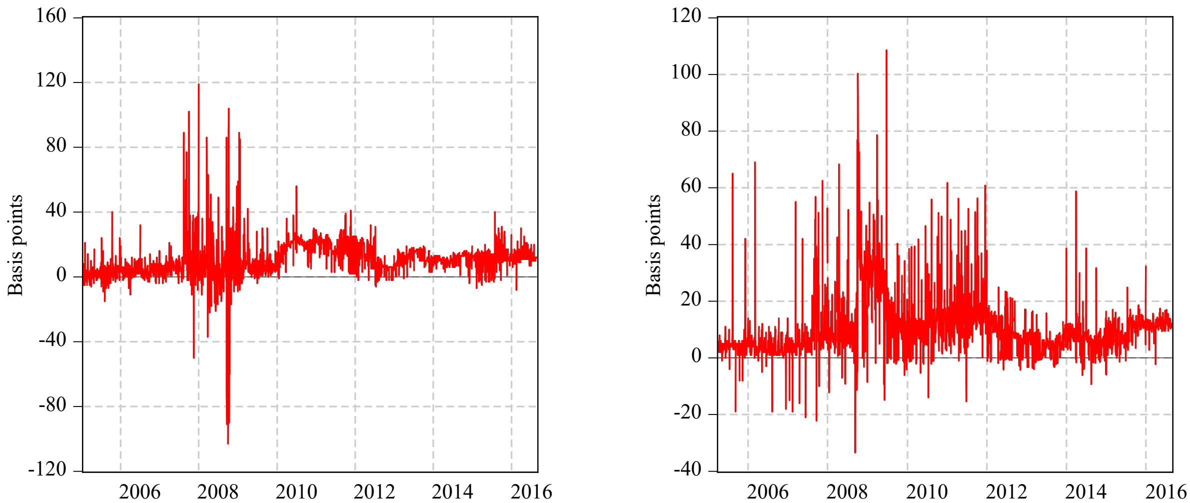
Figure 1.C.1
Using OIS contracts in CIP arbitrage



Notes: The graph shows the mechanics involved in using OIS contracts for CIP arbitrage. Solid lines represent transactions while dashed lines are interest rate payments. In the OIS, the fixed rate is not paid or received every day. It is a fixed rate where the net difference between the average of the floating rate and the fixed rate is settled on the termination date of the contract.

development that has encouraged the Federal Reserve Bank of New York to develop an alternative benchmark rate (Overnight Bank Financing Rate). This rate relies on eurodollar transaction data (see, e.g., Duffie and Krishnamurthy, 2016).

Figure 1.C.2
Roll over risk in OIS-based CIP arbitrage



(a) USD (b) EUR

Notes: The Figure show difference between overnight rates and the underlying overnight rate in the OIS contract measured in basis points. For USD, the underlying rate is the effective Fed funds rate, while for EUR it is the EONIA rate. The graphs show borrowing in USD (overnight ask rate minus effective Fed funds) in Panel (a) and lending in EUR (EONIA minus overnight bid rate) in Panel (b).

Figure 1.C.2 illustrates the rollover risk in OIS-based CIP arbitrage arising from the mismatch in the evolution of actual O/N borrowing rate faced by the arbitrageur and the movement of the underlying floating O/N rate in the OIS contract. As can be gleaned from the graph, this spread can widen significantly at times and can be quite volatile, suggesting that rollover risk can be quite material in discouraging OIS-based CIP arbitrage.[45]

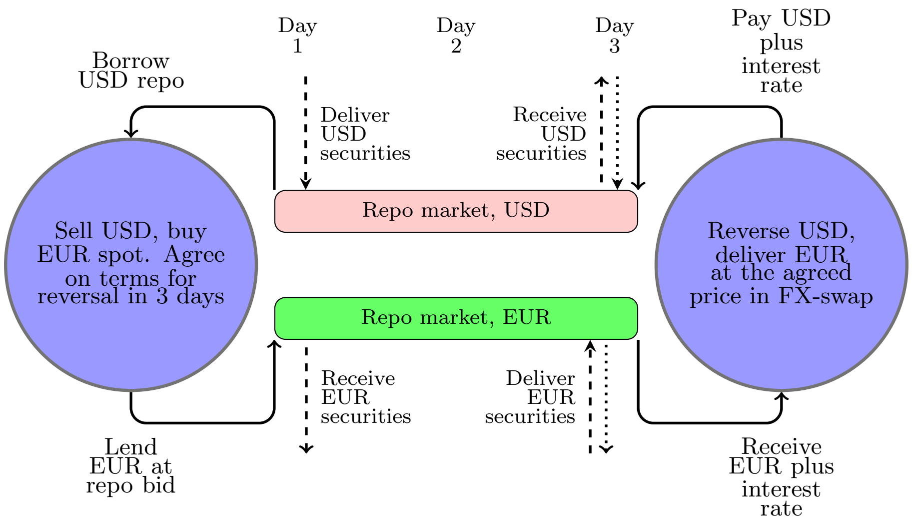
[45] The GFC is a primary example of evaporating funding liquidity characterised by a shortening of the maturity of funding, where it became highly expensive, and even virtually impossible, to roll over O/N funding. Instead of providing reserves in the O/N market, banks were hoarding reserves and arbitrageurs (hedge funds and proprietary trading desks in banks) found it difficult to even obtain O/N funding.

1.D CIP arbitrage with repo contracts

As discussed in the main text in Section 1.2.2, the cross-currency basis for risk-free interest rates has been different from zero also pre-crisis, in particular for repo rates. Tightening of banking regulation thus cannot be the sole explanation for the existence of the basis for repo rates (as well as for other risk-free rates such as T-Bills). As discussed in the main text, a non-zero repo-basis arises from how investors value the collateral in different currencies, also referred to as convenience yield. For these reasons, it is hard to argue that the existence of a repo basis truly represents arbitrage opportunities and the existence of a free lunch. In the following, we provide some further institutional background and arguments to make this case.

To give some background, Figure 1.D.1 illustrates the mechanism of using the repo market in CIP arbitrage.

Figure 1.D.1
Using repo contracts in CIP arbitrage



Notes: The Figure shows the mechanics involved in using repo contracts for CIP arbitrage. Solid lines represent transactions, while dashed lines depict interest rate payments/security transfers.

The following example may help shed further light on our argumentation in the main text why the use of repo rates in assessing arbitrage opportunities due to CIP deviations is not innocent. Imagine a bank with an initial portfolio endowment of both U.S. and German Treasury securities. These assets are unencumbered and obviously ultimately funded by unsecured financing. The bank can in principle repo out the U.S. Treasuries and obtain cash. When encumbered through a repo, the U.S. Treasuries serve as a vehicle to be exposed to potential interest rate risk, but cannot generate any more cash during the term of the repo. This means that it makes little difference to the bank whether it conducts a repo or sells U.S. Treasuries in order to obtain the necessary USD for the trade. When the Treasuries are sold, it is clear that the bank is left with cash financed by unsecured borrowing. The shadow cost of encumbering the collateral is the difference between the unsecured borrowing and the repo rate, plus the cost of a potential haircut.

Now imagine that the bank wants to benefit from a CIP deviation as indicated by the repo-basis. After having monetized the U.S. treasuries to repo dollar financing, the bank may then conduct an FX swap, swapping the dollars for EUR and engage in a reverse repo, receiving German Bunds as collateral. The bank can now raise cash in EUR by re-using its euro-denominated assets received in the repo, but the bank cannot raise U.S. dollars via the euro-denominated asset without going through the FX swap market again. What this sequence of trades shows is that the new EUR-denominated assets held by the bank are *effectively* financed by unsecured USD funding. This simple example shows that the secured funding cost via repo does not reflect the *marginal* funding cost in the CIP arbitrage. CIP deviations based on GC repo rates will therefore reflect cross-currency differences in the total costs of funding the collateral, rather than be an indication of a 'free lunch'.

Special repo. For the reasons above, when testing for the existence of arbitrage opportunities based on repo rates, it is therefore important to move beyond GC repo rates. A special repo needs to be considered where the arbitrageur delivers and receives collateral denominated in the *same* currency in both the borrowing and the investment currency. This does not alter the currency composition of the liquidity portfolio of the arbitrageur, and hence allows a comparison of "apples with apples". The interest rate quoted in a special repo, however, can be very different from that in a GC repo. The issue is exacerbated when the relative term funding premiums between the two currencies are different.[46]

Rehypothecation. There may be situations, however, where market participants are able to use collateral where their own unsecured funding cost is not the correct measure of the full marginal cost. This applies for example to custodians and a practice called rehypothecation. Rehypothecation means that the custodian has an agreement with the legal owner of the asset to use the collateral against a fee. This was common practice among U.S. custodians before 2008, but legal issues connected to rehypothecation and regulatory initiatives have reduced both the demand for and supply of this business in recent years. In any case, the fee the custodian has to pay must be incorporated in the cost of setting up a CIP arbitrage trade.

[46]Data on special repos are rare and difficult to obtain. We asked for a cross-currency OTC repo quote from a high-rated dealer via Norges Bank's money market desk. The dealer responded by saying that such a deal would have been priced based on FX swaps. This means that the dealer would need to add the cost of delivering a security denominated in the currency with a high funding liquidity premium equal to the cost of swapping cash into the same currency. This would obviously effectively eliminate any profit from the CIP trade.

1.E How do banks price funds internally?

We provide here some more details on the institutional background on how banks price and allocate funds internally, mentioned in Sections 1.3 and 1.4. An important concept of how banks determine the "internal price" when allocating funds across different divisions is *funds transfer pricing* (FTP). The treasury division is responsible for the bank's funding, its liquidity management and the internal pricing of funds to its different operations. One can think of the treasury division as a "bank within the bank": it buys funds from the divisions managing the liability side of the bank and sells funds to the divisions that invest in assets. The most commonly used method currently considered by practitioners is called matched-maturity funds transfer pricing.

The basic goal of FTP is to transfer interest rate risk and liquidity risk to a central location (the treasury unit) and make the booked income of the remaining units of the bank immune against these risk factors. Matched-maturity funds transfer pricing implies that the prices at which the treasury buys funds from its deposit-taking units and the prices it charges for funds transferred to units investing in banking assets are related to the cost of obtaining the funds. This means that the internal price also reflects the associated balance sheet costs for a given maturity.

To accomplish this task, the treasury unit constructs an interest rate curve, determining the funds transfer price for the full maturity spectrum. This curve incorporates the marginal cost of using funds across maturities. The use of a marginal cost interest rate curve enables the treasury unit to maintain all liquidity risk within the treasury department and price this risk accordingly (arising from maturity transformation).[47] Hence, the corresponding interest rate curve determines the appropriate price at which the treasury unit buys and sells funds such that the business units are left with the net interest margin arising from (i) the funding spread between deposit rates faced by the bank's customers (liability side) and the internal price, and (ii) the spread between the internal price and the return on the banking assets (asset side).

The crucial part of FTP is to construct the interest rate curve based on the marginal funding costs faced by the bank in a way that also reflects the balance sheet cost. A crude way of doing this is to use interbank deposit rates for tenors below one year and the Interest Rate Swap (IRS) curve beyond that.[48] The difference between the market swap curve based on interbank deposit rates and the final FTP curve determines the term structure of the funding liquidity premium. The reason for using deposit rates in FTP is that they are regarded as a reasonable proxy for the marginal cost of using funds for banks.

Globally active banks need to create a FTP curve in each of the currencies they are operating in. For example, a bank may establish a full interest rate curve in its main funding currency and then rely on the pricing in the FX swap market to create implied interest rate curves in the rest of the

[47] Liquidity transfer pricing is an integral part of funds transfer pricing (see Grant (2011)).

[48] It is more precise to construct the FTP curve by relying on the bank's own fixed-rate funding cost, stripped down to variable-rate marginal funding cost by an internal interest rate swap.

operating currencies. Alternatively, the bank could calculate a fully independent curve in each of the currencies. Regardless of the approach taken, the internal price of funds in different currencies has to be consistent with the implied interest rate one can achieve through the FX swap market. In case of a discrepancy, internal business units may otherwise exploit the inconsistency.[49]

Funds transfer pricing and the law of one price. The discussion above has major implications for investigating the law of one price in international money markets. As laid out above, the internal pricing of funds by banks needs to be closely aligned with the law of one price.[50] Interbank deposit rates reflect the general interest rate level in a currency, the term funding liquidity premium, the credit risk premium of the quoting bank, and the balance sheet cost of using additional funds. Interbank deposit rates thus exactly capture what banks' funds transfer price ought to represent as well. One may therefore expect that there is a tight empirical relationship between interbank deposit rates and the funds transfer price.

[49]For example, if the treasury pays business units more for currency A than it implicitly charges for the funds in currency B swapped into currency A by conducting an FX swap, business units may have an incentive to borrow currency B, conduct an FX swap in the market and sell currency A back to the treasury unit.

[50]Of course, the bank's treasury unit may be in a position to look for the relative value of funding in different currencies. One should also point out that the exact implementation of FTP may vary across banks. That said, the main principles remain largely intact.

1.F Liquidity premia in international money markets

This section provides some further background and illustration regarding the evolution of funding liquidity premia across currencies. It is useful conceive of the unsecured marginal funding cost of bank j in USD, $r_{j;\$}$ (suppressing the t subscript) as

$$r_{j;\$} = r^f_\$ + cr_j + \widetilde{lp}_\$, \tag{1.18}$$

where $r^f_\$$ is the USD risk-free rate, cr_j denotes a compensation for credit risk (assumed constant across currencies for global banks) and $\widetilde{lp}_\$$ stands for the liquidity premium in USD.

It is worth illustrating the importance of funding liquidity premia based on a simple proxy. First, we insert the OIS rate as a proxy for the risk-free rate in Equation (1.18), and, second, assume that the credit component faced by a particular bank j is the same across currency areas. Taking the difference in the marginal funding spread $(r_j - r^{OIS})$ across the two currencies will then filter out the credit component and give us a measure of the *relative* liquidity premium differential,

$$\widetilde{lp}_\$ - \widetilde{lp}_\star = \left(r_{j;\$} - r^{OIS}_\$\right) - \left(r_{j;\star} - r^{OIS}_\star\right), \tag{1.19}$$

between USD and the foreign currency. This simple measure can be averaged over bank-specific data, or, as we do, over CP-spreads for different rating categories, to minimize noise.

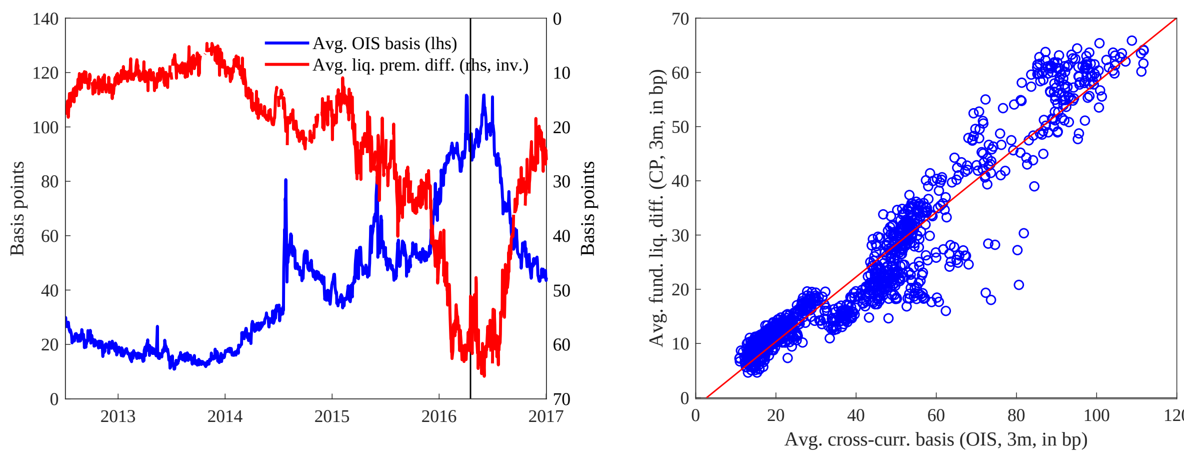
For ease of reference, we also define the cross-currency basis computed from OIS rates (in short "OIS-Basis") as follows

$$OIS\text{-}Basis = \frac{F}{S}\left(1 + r^{OIS}_\star\right) - \left(1 + r^{OIS}_\$\right). \tag{1.20}$$

Figure 1.F.1 illustrates that funding premium differentials (between the USD and other currencies) and the OIS-Basis are highly correlated. In Panel (a) the blue line shows the time series of the OIS-Basis (positive number suggests deviation) together with the liquidity premium differential vis-à-vis the USD in red (both averaged across currencies). The latter is constructed based on CP rates following Equation (1.19) outlined above. Panel (b) depicts the cross-plot of the cross-currency basis with OIS rates and the average liquidity premium differential across currencies vis-à-vis the USD.

The fact that proxies for the relative funding liquidity premium exhibit fluctuations that closely resemble those in the OIS-Basis indicates that funding strains in USD markets are a primary driver of both the premium to obtain USD in the FX swap market and funding spreads in U.S. money markets. The vertical line marks the implementation date of the U.S. money market fund reform—a major disruption to USD funding markets. Both time-series—our measure of the relative funding liquidity premium in the USD compared to other major currencies and the cross-currency basis for OIS rates—have their peak around this event and fluctuate quite closely together (liquidity premium

Figure 1.F.1
Funding liquidity premia and the cross-currency basis



(a) Cross-currency OIS basis and funding liquidity premium differentials

(b) Cross-currency OIS basis vs. funding liquidity premia (b.p)

Notes: The Figure illustrates the relationship between funding liquidity premia and the cross-currency basis (3-month maturity). The cross-currency basis is calculated from OIS rates. Panel (a) compares the time series of the 3-month OIS-basis (left-hand axis) with the average funding liquidity differential based on CP-rates (right-hand axis, inverted scale). The vertical line in Panel (a) indicates October 14, 2016, the date of the implementation of the U.S. Money Market Fund reform. Panel (b) shows a scatter-plot for the average 3-month cross-currency basis based on OIS rates (horizontal axis) together with average funding liquidity premium differentials vis-à-vis USD (vertical axis) based on CP rates. Averages are across EUR, CHF and JPY. Sample: January 2013 – June 2017.

differential on inverse axis on the right).

What this evidence suggests is that OIS-based LOOP violations largely reflect fluctuations in the *relative* difference in term funding liquidity premia across currencies. Based on this interpretation, a widening of the OIS cross-currency basis is not necessarily an indication of arbitrage profits, but rather suggests that the costs of USD term funding (relative to other currencies) have firmed.

1.G Regulations and the FX swap market

This section gives some further background on the impact of banking regulations on developments in FX swap markets, especially around regulatory reporting dates (notably, quarter-end and year-end). An important question is whether short-term (in particular, 1-week and 1-month) LOOP violations around quarter- and year-end reporting days can be attributed to the tightening of banking regulations following the GFC, hampering banks ability to sufficiently exploit the arbitrage. Such spikes, documented in the recent work of Du et al. (2019), provide compelling evidence of banks' window dressing behavior (also see Krohn and Sushko (2017) and Abbassi and Bräuning (2018)). The uneven application of the leverage ratio across jurisdictions—with some jurisdictions requiring reporting on a period-average basis and others as a period-end snapshot—undoubtedly creates extreme outcomes in FX swap markets around reporting dates.

Several pieces of evidence suggest, however, that a mono-causal explanation based on regulation as the single driver is insufficient but that quarter- and year-end spikes arise due to a confluence of factors. A first piece of evidence relates to the timing of law of one price deviations. The fact that there have been sizeable deviations from the law of one price for repo rates and T-bills already *prior* to the GFC, as shown in Figure 1.3 above and discussed in Section 1.2, suggests that law of one price deviations in international money markets are not limited to the period of tighter banking regulation post-crisis.

A crucial factor that has played a role, in conjunction with regulation, has been the strong increase in excess liquidity as central banks' heavily expanded their balances sheets via asset purchases. An important reason for the relation between end-of-quarter spikes and abundance of liquidity is that for regulatory reporting purposes, an FX swap is treated as an off-balance sheet item (as opposed to repos, for instance, which increase the size of the balance sheet, see Borio et al. (2017)). This means that a globally active bank holding (excess) EUR liquidity on its balance sheet, can lend it out via an FX swap in exchange for USD. The result is that the cash held in EUR is replaced with USD cash on the balance sheet. If the bank simultaneously lets its USD borrowing mature and uses the USD cash obtained via the swap to pay down the debt, the consolidated balance sheet of the bank will be reduced. Figure 1.G.1 illustrates the balance sheet effects. Due to such incentives, excess liquidity in EUR, JPY, and CHF is just waiting to be deployed in the FX swap market around major reporting dates, with the aim of reducing banksâ balance sheets.

Corroborating the important role played by the evolution of excess liquidity in different currency areas, Figure 1.G.2 shows that fluctuations in 1-week LOOP violations and quarter-end and year-end spikes started to emerge when excess liquidity increased on the back of central bank balance sheet expansion. In fact, in several cases the spikes in CIP deviations could already be observed prior to the implementation of tighter banking regulations. The vertical lines indicate key dates associated with a significant rise in central banks' balance sheets (the ECB's public sector asset

Figure 1.G.1
Window-dressing involving FX swaps: Two balance sheet scenarios

Assets	Liabilities	FX swap:	Assets	Liabilities	Pay down	Assets	Liabilities
Cash 100	100 Deposit	-100/	**Cash $100**	100 Deposit	ST debt	**Cash 0**	100 Deposit
Loan $100	$100 ST. debt	+$100	Loan $100	$100 ST. debt	in $	Loan $100	**0 ST. debt**
Total 200	200 Total	$\Rightarrow$	Total 200	200 Total	$\Rightarrow$	Total 100	100 Total

(a) Balance sheet reduction via FX swaps seen from a EUR-rich bank (assuming EURUSD FX rate is 1

Assets	Liabilities	Borrow	Assets	Liabilities	FX swap:	Assets	Liabilities
Cash $0	$100 Deposit	to do	**Cash $100**	$100 Deposit	-$100/	**Cash 100**	$100 Deposit
Loan $200	$100 ST. debt	arb	Loan $200	**$200 ST. debt**	+100	Loan $200	$200 ST. debt
Total $200	$200 Total	$\Rightarrow$	Total $300	$300 Total	$\Rightarrow$	Total $300	$300 Total

(b) USD-financed arbitrage

Notes: Panel (a) shows the balance sheet impact by swapping from EUR to USD to reduce debt for the purposes of window-dressing. Panel (b) shows balance sheet impact by increasing USD debt to open an arbitrage position.

purchase program, the Bank of Japan's quantitative and qualitative easing, and in the case of the Swiss National Bank, the introduction of the EUR/CHF floor regime). The spikes, almost all aligned with quarter-end periods, typically started to emerge in the period after the substantial rise in central bank reserve balances. In the case of the CHF, a few spikes occur prior to implementation of the exchange rate peg with the EUR. A likely reason is the Swiss National Bank's efforts to fight the appreciation of the currency via (unsterilized) FX interventions and provision of central bank reserves through collateralized loans, which significantly expanded the CHF reserve balances held by commercial banks. In the case of EUR, a few spikes occur in relation to ECB's liquidity-measures during the EUR-crisis in 2011 and 2012 which resulted in a large expansion of reserve balances. Table 1.G.1 presents a regression analysis showing that end-of-quarter effects were not present prior to the introduction of QE by major foreign central banks.

Table 1.G.1
Quantitative Easing (QE) and End-of-Quarter effects

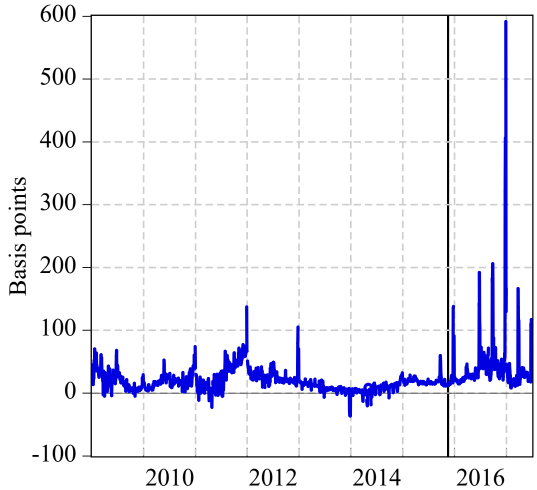
	CHF	EUR	JPY	Panel
EoQ during QE	0.343	0.862	0.635	0.526
	(3.27)	(3.90)	(3.85)	(5.62)
EoQ pre-QE	-0.022	0.006	0.014	0.003
	(-0.54)	(0.19)	(0.55)	(0.24)
Obs.	2,192	2,186	2,192	6,570
adj.R^2	0.05	0.16	0.12	0.09

Notes: Regression of 1-week IBOR LOOP violations on dummy for End-of-Quarter-period, interacted with dummy for before and after implementation of Quantitative Easing (QE). Constants and fixed effects supressed. Sample: January 2009 – June 2017.

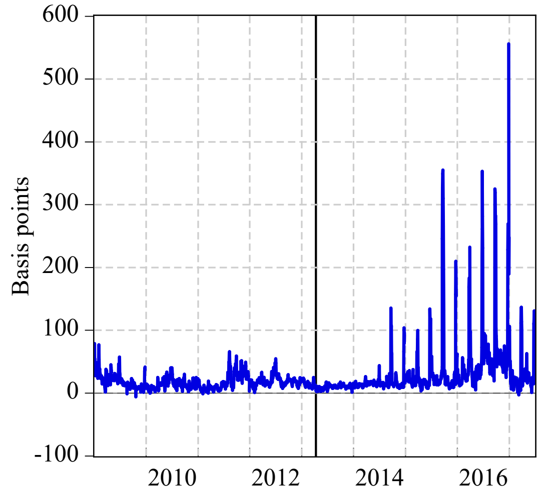
Another piece of evidence relates to the extent that regulations have hampered banks ability exploit arbitrage in international money markets. Evidence from banks' own balance sheets suggests that constraints have been rarely binding outside of reporting dates. As trading the cross-currency repo basis is close to risk-free, the most relevant regulatory constraint for banks engaging in such a trade is the leverage ratio. The leverage ratio discourages low margin and leveraged trades. Repo intermediation—or "matched book repos"—also falls into this category as the business is based on a dealer passing on cash and high quality collateral denominated in the same currency between its counterparties against a small margin (typically 5-10 basis points). When it comes to regulatory implications, such repo intermediation is very similar to the type of arbitrage involved in exploiting the cross-currency basis in repo rates.

Both types of trades increase leverage at low risk (and low return). But, the main difference is that when arbitraging the cross-currency repo basis, unlike the case of matched book repo inter-

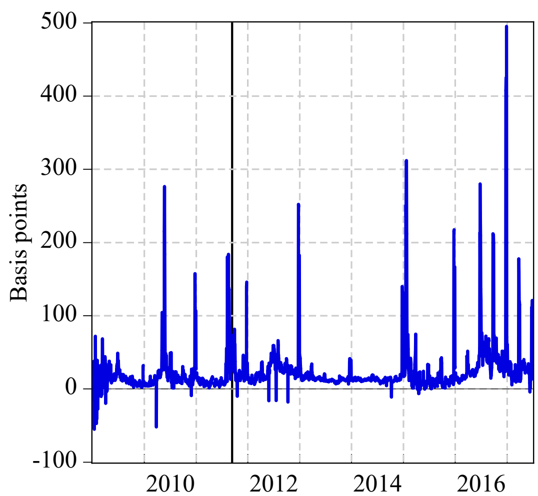
Figure 1.G.2
LOOP violations, End-of-Quarter effects and implementation of QE



(a) EUR



(b) JPY

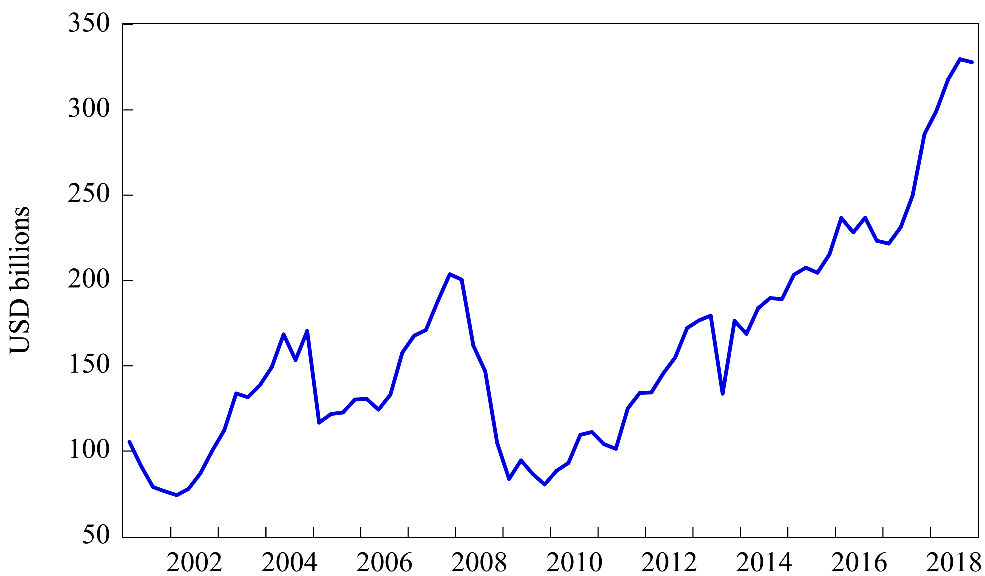


(c) CHF

Notes: The Figure shows fluctuations in 1-week LOOP deviations (based on LIBOR rates). Positive values indicate that the synthetic LIBOR rate (FX swapped from EUR, JPY and CHF) is higher than the direct LIBOR rate in the U.S. The vertical lines indicate key dates associated with large-scale central bank balance sheet expansion that led to a substantial rise in reserve balances in the three currency areas (introduction of QQE in Japan, PSPP in the euro area and the introduction of the CHF/EUR floor system). Sample: Jan 2009 — July 2017.

mediation, the funding currency is *different* from the investment currency. That is, the collateral received in the investment leg (typically JPY or EUR) is denominated in a different currency than the funding (mainly the U.S. dollar). Since matched book repo activity consumes balance sheet one would expect this activity to fall should the leverage ratio act as a binding constraint. However, figure 1.G.3 indicates that foreign bank holding companies in U.S. instead have significantly increased their matched book repo intermediation activity steadily since 2010 (during a period of tightening of regulation).[51] This suggests that globally active banks must also have balance sheet capacity to perform cross-currency repo basis arbitrage as well. There are other factors, however, that prevent the arbitrage from being fully exploited—especially the fact that the foreign collateral constitutes an additional cost on top of the GC repo rate when financing the cross-currency repo basis.

Figure 1.G.3
Developments in the size of the matched repo-book by major foreign banks



Notes: The Figure depicts a proxy for matched book repo activity in USD among foreign bank offices and is calculated as the sum of the repo-holdings of foreign bank offices balance sheets in the U.S. that are matched on both sides on the balance sheet. A bank with 10 billion USD on repo liabilities and 20 billion repo assets will be assigned 10 billion USD in matched book repo-holdings. The numbers are in USD billions. Source: U.S. call reports (FFIEC 002).

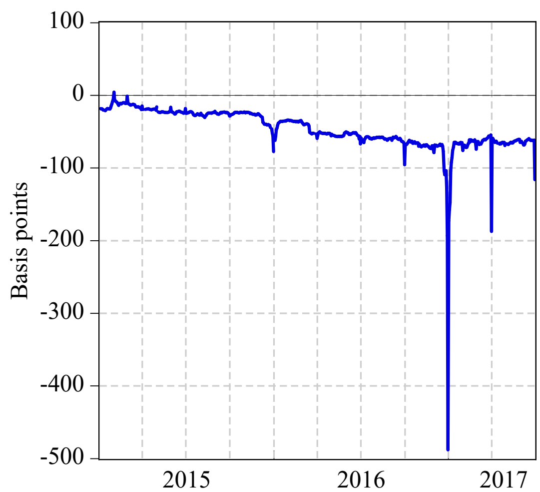
Finally, for some of those banks that do have balance-sheet capacity to engage into arbitrage, it will in fact not be profitable given the investment opportunities that they have access to. As we showed in the main text, some of arbitrage flow (supplying USD at a premium in the FX swap markets against EUR, CHF or JPY) will be profitably invested at the deposit rate offered by the

[51] It is indeed true that foreign bank holding companies reduce the repo activity significantly over reporting dates, but the quarterly *average* activity, as shown in Figure 1.G.3, has increased notably in spite of regulatory tightening.

foreign central bank (see the evidence presented in Section 1.4 and Figure 1.6). But, for banks or other opportunistic players that do not have access to the central bank deposit facility, the only risk-free investment alternatives available will be short-term reverse repos and T-bills that mature right after year-end/quarter-end. Importantly, however, the pricing of these investment vehicles (unlike the rate of remuneration on central bank deposits) responds to volume, thereby reducing possible arbitrage profits. Given that collecting data on all bonds that mature right after reporting days is difficult, Figure 1.G.4 shows an example of a typical price response of a German Treasury bill that, given its maturity profile, would be suitable as a risk-free investment vehicle around such an episode. The Figure shows that the T-bill yield drops significantly, in turn making the arbitrage less attractive. In Panel (b) we show that EUR GC repo rates also have significant drops around quarter-end and year-end.

Figure 1.G.4
Two examples of German investment rates around regulatory reporting

(a) Treasury

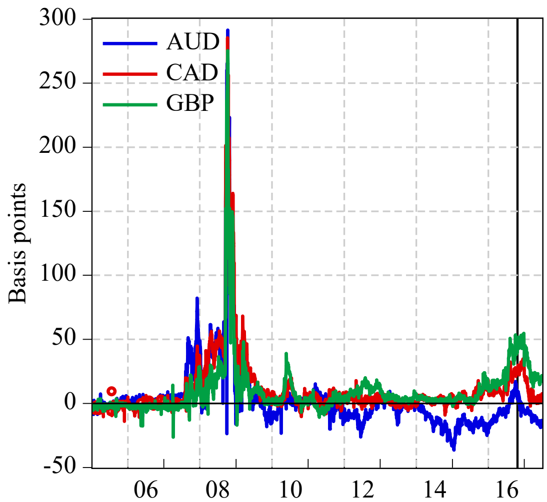


(b) Repo

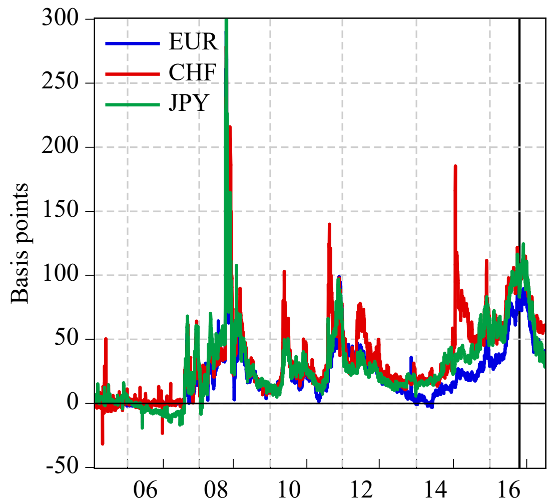
Notes: Panel (a) shows the interest rate on a German Treasury bill (BUBILL 0 01/10/18) maturing on January 10, 2018. Panel (b) shows the euro General Collateral (GC) repo rate for collateral issued only by the German government. The index is calculated from trades executed on either the BrokerTec or the MTS electronic platform and all transactions are centrally cleared. The data is published by NEX Data.

1.H Supplementary Tables and Figures

Figure 1.H.1
Cross-currency basis with OIS rates



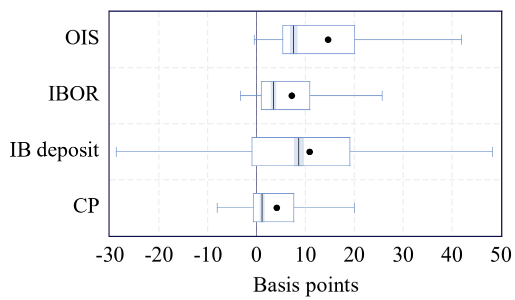
(a) AUD, CAD, GBP



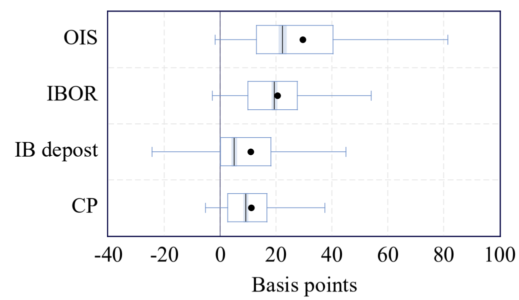
(b) EUR, CHF, JPY

Notes: The Figure shows the evolution of profits from roundtrip cross-currency basis trades (measured in basis points) involving USD borrowing (USD interest rate at the ask rate), using 3-month OIS rates. All legs of the roundtrip cross-currency trade (rates and FX swaps) are adjusted for bid-ask spreads (as described in the text). Panel (a) shows trading profits for AUD, CAD and GBP, while Panel (b) depicts the corresponding profits for EUR, CHF and JPY. Axis capped at 300bp for readability. The maximum was just above 400bp for JPY during October 2008. The vertical line indicate October 14, 2016, the date of the implementation of the U.S. Money Market Fund reform.

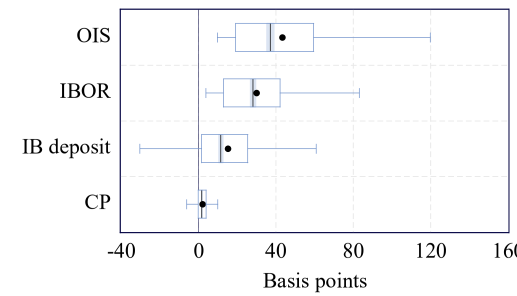
Figure 1.H.2
LOOP deviations for different money market rates



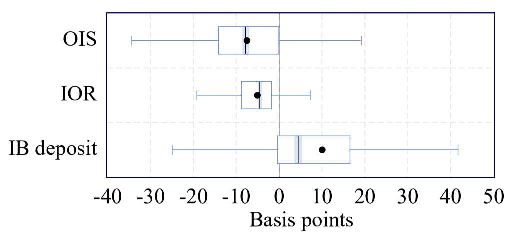
(a) GBP



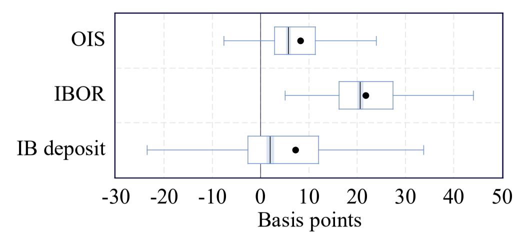
(b) EUR



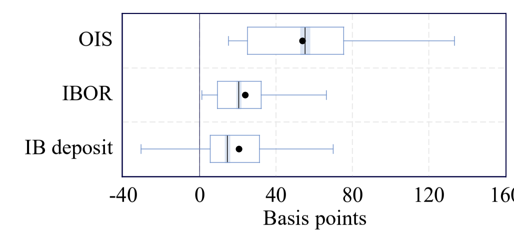
(c) JPY



(d) AUD



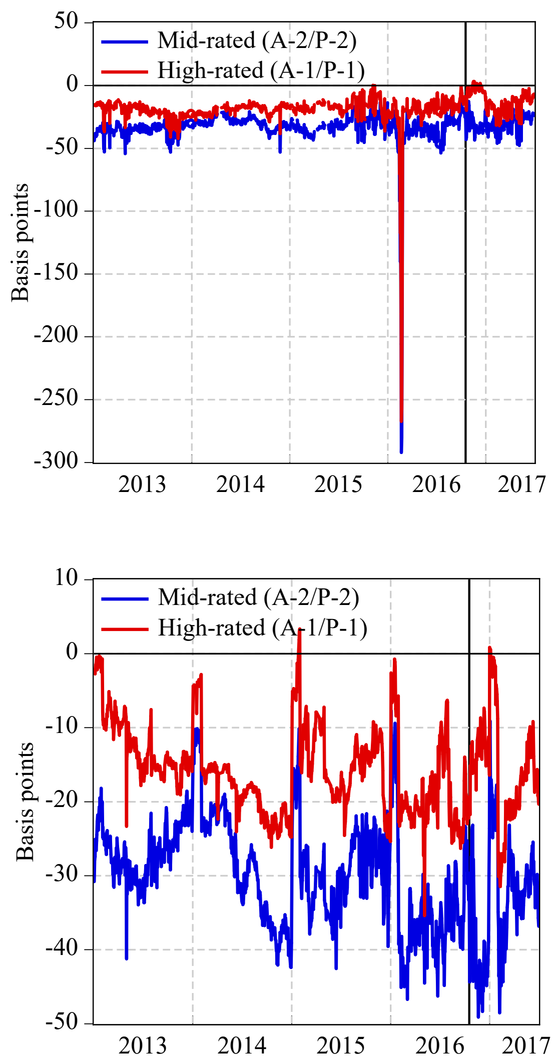
(e) CAD



(f) CHF

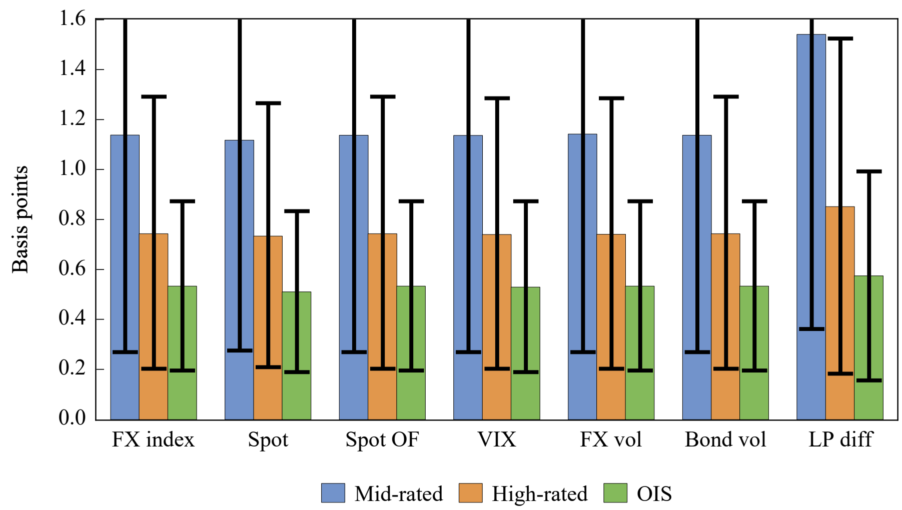
Notes: The Figure shows box plots of LOOP deviations for different 3-month money market rates. The depicted LOOP deviations compare the direct FCU rate and the implied rate by swapping from USD. For ease of exposition, the average across the currencies for which we have CP rates (EUR, JPY, and GBP) is shown and LOOP deviations for CP rates are averaged across rating-categories. LOOP violations are measured in basis points. Elements of the box plot are as follows: the staples (end of straight line) represent value of last data point; the box itself represents the first and third quartile; inside the box, the mean is represented by a dot, while the median is represented by a line; the shaded area around median represents 95% confidence interval. Sample: January 2013 – June 2017.

Figure 1.H.3
Risk-free 3-month CIP arbitrage opportunities. Average over AUD, CAD, and GBP

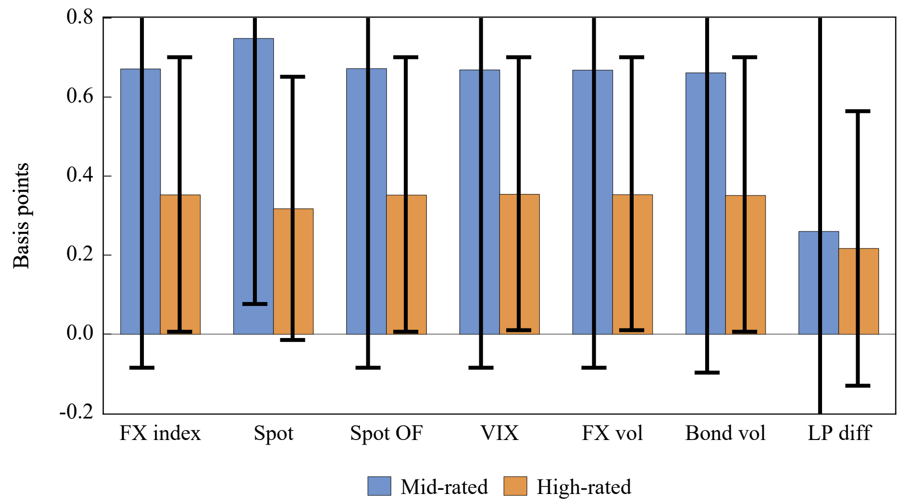


Notes: The Figure shows risk-free CIP arbitrage profits for global banks when funded via the issuance of USD commercial paper, swapping into foreign currency, and investing the funds in the foreign Treasury bills (Panel (a)) or central bank deposits (Panel (b)). Funding rates differ for mid-rated banks (A-2/P-2) and high-rated banks (A-1/P-1). The vertical lines indicates October 14, 2016, the date of the implementation of the U.S. Money Market Fund reform. Sample: January 2013 – June 2017.

Figure 1.H.4
Impact of FX swap order flow for alternative specifications



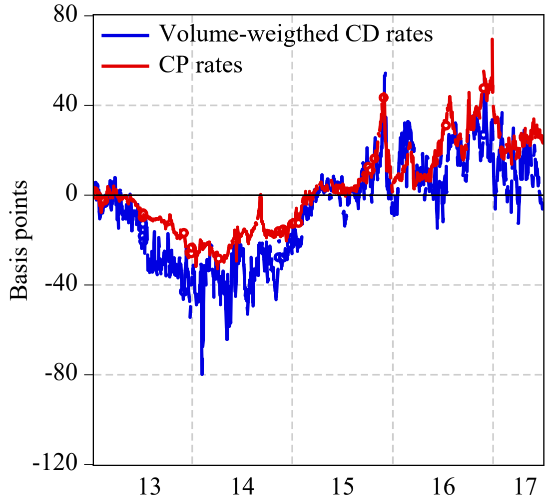
(a) Central bank deposit investment and OIS-basis



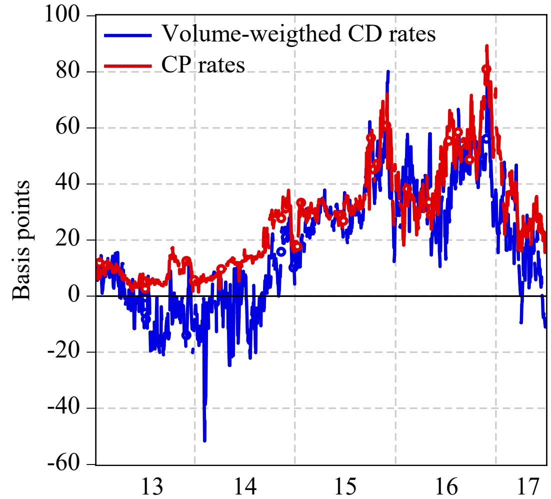
(b) Treasury bill investment

Notes: The Figure shows the impact of (standardized) swap order flow on CIP arbitrage profits (3-month maturity), conditioned on being in a positive arbitrage state, for different model specifications. Vertical lines indicate $\pm$ 2 $\times$ coefficient standard errors, which are symmetric but truncated at top and bottom if they reach outside graph area. Panel (a) shows alternatives with CIP deviations using central bank deposits as investment (as in c), or OIS basis. Panel (b) shows results for T-bills as the investment-leg in the CIP-arbitrage. The seven alternative models are as follows (from left): (i) Using a broad FX index (for panel (a) same as 1.4); (ii) replacing the FX index with bilateral spot exchange rates; specifications (iii)-(vii) adds different variables to the benchmark model in (i), like VIX, FX volatility represented by the VXY index, bond market volatility represented by MOVE index, and our measure of liquidity premium differentials. Sample for estimation: January 2013 – June 2017.

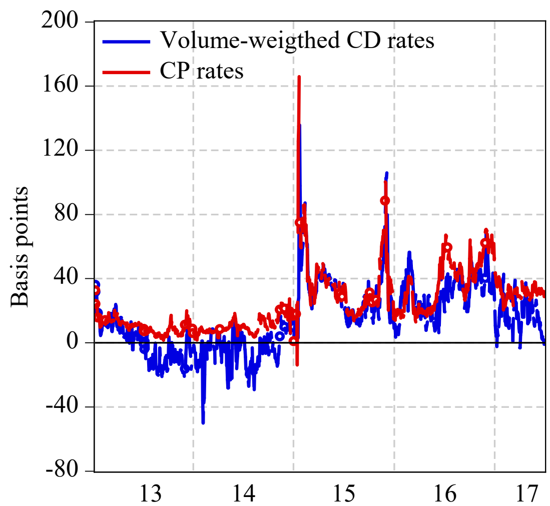
Figure 1.H.5
CIP arbitrage profits using CP rates vs. volume-weighted CD rates



(a) EUR



(b) JPY



(c) CHF

Notes: The Figure compares 3-month CIP arbitrage profits (in basis points) when investing in central banks deposits, for high-rated banks (A-1/P-1) using different sources of funding. The comparison is between funding either using CP rates or (5-day moving average of) the volume-weigthed CD rates faced on the issue date. Sample: Jan 2010 – July 2017.

Table 1.H.1
Comparison of CP spreads across currencies. 1-week and 1-month maturity

	Mean	Median	Std. Dev.	Obs.
		A: Commercial paper		
		Mid-rated banks (A-2/P-2)		
(i) 1-month				
EUR	-3.84	-1.60	7.75	1,102
GBP	4.50	4.60	4.13	1,103
JPY	-22.65	-18.18	20.94	1,045
USD	13.37	12.20	6.67	1,099
(ii) 1-week				
EUR	-5.80	-6.10	5.24	1,070
GBP	-0.54	-0.20	4.25	1,093
JPY	-9.34	-6.48	12.55	368
USD	8.98	6.90	10.60	1,092
		High-rated banks (A-1/P-1)		
(i) 1-month				
EUR	-10.41	-9.50	6.58	1,106
GBP	-4.04	-2.70	5.56	1,103
JPY	-38.50	-29.26	36.31	1,099
USD	4.27	3.90	3.33	1,099
(ii) 1-week				
EUR	-17.47	-14.60	20.85	998
GBP	-10.15	-6.60	21.33	957
JPY	-37.35	-25.90	74.68	924
USD	-0.96	-0.60	2.88	1,052

Notes: The Table presents summary statistics for money market spreads across currencies (for 1-week and 1-month maturities). Panel A provides summary statistics for the difference between commercial paper (CP) rates and OIS rates across two different rating categories, high-rated (A-1/P-1) and mid-rated (A-2/P-2), ie. $i^j - i^{OIS}$, $j \in \{\text{A-1/P-1, A-2/P-2}\}$. All rates are measured as ask (offer) rates and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017.

Table 1.H.1
(Continued) Comparison of money market spreads across currencies. 1-week and 1-month maturity

	Mean	Median	Std. Dev.	Obs.
		B: IBOR interbank rates		
(i) 1-month				
AUD	9.71	10.50	7.55	1,173
CAD	28.49	25.40	7.39	1,130
CHF	-17.51	-23.20	13.36	1,137
EUR	1.52	2.40	3.37	1,150
GBP	5.07	4.92	2.00	1,137
JPY	0.62	1.30	2.96	1,137
USD	6.66	6.30	2.37	1,136
(ii) 1-week				
CAD	-0.66	-0.50	0.25	1,174
EUR	-1.87	-2.00	2.55	1,150
GBP	2.89	2.67	1.61	1,137
JPY	-0.95	-0.49	3.00	1,137
USD	2.22	2.09	1.82	1,137
		C: Interbank deposit rates		
(i) 1-month				
AUD	35.03	34.40	17.89	1,173
CAD	18.84	15.00	12.66	1,174
CHF	-11.53	-10.00	19.56	1,174
EUR	4.33	3.50	4.94	1,174
GBP	16.30	16.53	8.44	1,174
JPY	-0.05	3.60	11.28	1,174
USD	18.68	15.20	11.80	1,173
(ii) 1-week				
AUD	23.45	22.50	16.56	1,173
CAD	14.31	12.00	13.06	1,174
EUR	2.16	1.20	5.22	1,174
GBP	9.72	7.70	5.36	1,174
JPY	-0.14	1.90	18.74	1,174
USD	12.59	12.70	7.04	1,174

Notes: The Table presents summary statistics for money market spreads across currencies. Panel B-C presents descriptive statistics on the difference between various interbank funding rates and OIS rates. All rates are measured as ask (offer) rates and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017.

Table 1.H.2
Roundtrip cross-currency basis arbitrage with OIS rates. 3-month maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
	Direction	Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
AUD	$FCU \Rightarrow USD$	7.9	9.5	68	57	847	2.1	9.2	65	39	326
	$USD \Rightarrow FCU$	-12.3	9.3	13	7	847	-6.2	7.7	24	15	325
CAD	$FCU \Rightarrow USD$	-8.1	4.5	0	0	848	-17.2	9.7	0	0	326
	$USD \Rightarrow FCU$	3.0	4.4	79	51	848	12.4	9.6	99	88	325
CHF	$FCU \Rightarrow USD$	-34.0	26.9	0	0	848	-89.4	19.6	0	0	326
	$USD \Rightarrow FCU$	25.1	24.8	100	100	848	80.3	18.6	100	100	325
EUR	$FCU \Rightarrow USD$	-19.2	10.6	0	0	846	-60.1	17.8	0	0	326
	$USD \Rightarrow FCU$	15.4	10.4	97	90	846	57.6	17.3	100	100	325
GBP	$FCU \Rightarrow USD$	-8.3	4.8	0	0	847	-33.7	12.9	0	0	326
	$USD \Rightarrow FCU$	3.9	4.6	99	85	848	26.0	12.4	100	100	324
JPY	$FCU \Rightarrow USD$	-25.3	16.9	0	0	848	-80.1	24.3	0	0	326
	$USD \Rightarrow FCU$	22.2	16.4	100	100	848	74.5	24.2	100	100	325

Notes: The Table presents summary statistics for the 3-month cross-currency basis with OIS rates (measured in basis points) for currencies against USD. The cross-currency basis is adjusted for transaction costs as outlined in the text and is sampled daily. The "Direction" column indicates if the roundtrip goes from USD, swapped into Foreign Currency ("$USD \Rightarrow FCU$"), or to USD, swapped into USD ("$FCU \Rightarrow USD$"), at the spot leg of the swap. As FX quotes differ by the base currency, for AUD, EUR and GBP "$USD \Rightarrow FCU$" involves the bid side of the swap, while for others it involves the ask side. Positive numbers in the "Median" column implies that a roundtrip trade would have been profitable if OIS rates adequately captured the arbitrageurs' funding costs and the rate at which the swapped funds can be placed. "Std.dev" is standard deviation. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table 1.H.2
(Continued) Roundtrip cross-currency basis arbitrage with OIS rates. 1-week and 1-month maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
	Direction	Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 1-month					
AUD	$FCU \Rightarrow USD$	4.1	12.5	65	49	847	-1.8	10.4	42	15	326
	$USD \Rightarrow FCU$	-8.9	11.5	20	6	846	-4.6	9.0	31	16	326
CAD	$FCU \Rightarrow USD$	-10.1	5.8	1	0	848	-20.7	11.5	0	0	326
	$USD \Rightarrow FCU$	3.7	5.8	81	45	847	13.7	11.2	98	73	326
CHF	$FCU \Rightarrow USD$	-30.1	33.6	0	0	848	-83.1	34.0	0	0	326
	$USD \Rightarrow FCU$	21.1	30.1	100	100	847	73.5	32.0	100	100	326
EUR	$FCU \Rightarrow USD$	-18.7	11.8	0	0	848	-58.4	27.5	0	0	326
	$USD \Rightarrow FCU$	14.6	11.3	95	87	847	53.7	26.7	100	100	326
GBP	$FCU \Rightarrow USD$	-9.4	6.7	0	0	848	-37.4	21.0	0	0	326
	$USD \Rightarrow FCU$	4.0	6.5	95	74	847	29.9	19.9	100	100	326
JPY	$FCU \Rightarrow USD$	-24.7	22.1	0	0	848	-72.2	43.2	0	0	326
	$USD \Rightarrow FCU$	19.1	21.0	100	100	847	60.0	42.5	100	94	326
						B. 1-week					
AUD	$FCU \Rightarrow USD$	-4.2	13.4	34	4	847	-9.1	13.8	18	0	326
	$USD \Rightarrow FCU$	-10.8	14.2	17	3	847	-10.1	11.9	13	0	326
CAD	$FCU \Rightarrow USD$	-12.3	8.4	4	0	848	-23.7	23.1	0	0	326
	$USD \Rightarrow FCU$	2.5	7.3	65	15	848	7.6	22.0	77	31	326
EUR	$FCU \Rightarrow USD$	-20.2	14.7	2	0	848	-44.9	64.2	0	0	326
	$USD \Rightarrow FCU$	11.1	11.8	94	72	848	32.2	55.7	100	100	326
GBP	$FCU \Rightarrow USD$	-10.6	13.5	0	0	848	-29.1	49.1	0	0	326
	$USD \Rightarrow FCU$	1.9	12.6	69	27	848	14.2	42.9	93	74	326
JPY	$FCU \Rightarrow USD$	-24.3	46.3	0	0	848	-54.9	78.6	0	0	326
	$USD \Rightarrow FCU$	12.0	32.4	98	81	848	23.5	63.7	92	46	325

Notes: The Table presents summary statistics for the 1-month and 1-week cross-currency basis with OIS rates (measured in basis points) for currencies against USD. The cross-currency basis is adjusted for transaction costs as outlined in the text and is sampled daily. The "Direction" column indicates if the roundtrip goes from USD, swapped into Foreign Currency ("$USD \Rightarrow FCU$"), or to USD, swapped into USD ("$FCU \Rightarrow USD$"), in the spot leg of the swap. As FX quotes differ by the base currency, for AUD, EUR and GBP "$USD \Rightarrow FCU$" involves the bid side of the swap, while for others it involves the ask side. Positive numbers in the "Median" column implies that the median roundtrip trade would have been profitable if OIS rates adequately captured the arbitrageurs' funding costs and the rate at which the swapped funds can be placed. "Std.dev" is standard deviation. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 –

Table 1.H.3
Roundtrip cross-currency basis arbitrage with interbank deposit rates. 1-week and 3-month maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
	Direction	Median	Std.	Deviation (%D)	(%M)	Obs	Median	Std.	Deviation (%D)	(%M)	Obs
						A. 3-month					
AUD	$FCU \Rightarrow USD$	-15.5	9.2	1	0	848	-41.3	19.7	0	0	326
	$USD \Rightarrow FCU$	-11.5	8.9	9	0	848	11.0	19.1	67	17	326
CAD	$FCU \Rightarrow USD$	-13.4	8.3	2	0	848	-41.8	21.6	2	0	326
	$USD \Rightarrow FCU$	-13.0	8.6	6	0	848	6.7	20.8	61	12	326
CHF	$FCU \Rightarrow USD$	-24.2	13.7	1	0	848	-60.6	18.7	0	0	326
	$USD \Rightarrow FCU$	-12.3	10.1	11	0	848	16.2	19.8	72	19	326
EUR	$FCU \Rightarrow USD$	-14.7	8.9	1	0	848	-43.6	18.4	0	0	326
	$USD \Rightarrow FCU$	-9.8	9.1	11	0	848	18.5	19.3	73	30	326
GBP	$FCU \Rightarrow USD$	-17.1	11.3	3	0	848	-43.9	17.6	0	0	326
	$USD \Rightarrow FCU$	-11.6	10.4	7	0	848	9.5	19.0	65	16	325
JPY	$FCU \Rightarrow USD$	-20.8	12.0	1	0	848	-48.4	19.7	0	0	326
	$USD \Rightarrow FCU$	-9.6	9.7	17	0	848	8.6	20.6	65	8	326
						B. 1-week					
AUD	$FCU \Rightarrow USD$	-18.0	15.6	1	0	848	-30.8	20.5	2	0	326
	$USD \Rightarrow FCU$	-15.9	13.9	3	0	848	-18.9	19.5	13	0	326
CAD	$FCU \Rightarrow USD$	-17.1	11.0	1	0	848	-42.0	27.5	0	0	326
	$USD \Rightarrow FCU$	-15.6	8.3	4	0	848	-5.3	26.4	35	0	326
CHF	$FCU \Rightarrow USD$	-24.2	35.8	0	0	848	-47.6	63.6	2	0	326
	$USD \Rightarrow FCU$	-14.8	26.8	5	0	848	-6.5	53.9	40	0	326
EUR	$FCU \Rightarrow USD$	-16.2	15.9	3	0	848	-43.5	63.8	0	0	326
	$USD \Rightarrow FCU$	-9.3	12.7	17	0	848	10.5	55.1	69	7	326
GBP	$FCU \Rightarrow USD$	-13.9	15.7	1	0	848	-38.7	51.6	0	0	326
	$USD \Rightarrow FCU$	-12.5	14.4	7	0	848	-1.0	43.3	49	4	326
JPY	$FCU \Rightarrow USD$	-21.7	39.6	1	0	848	-52.1	69.1	1	0	326
	$USD \Rightarrow FCU$	-9.0	26.8	17	0	848	0.4	59.1	50	0	325

Notes: The Table presents summary statistics for the 3-month and 1-week cross-currency basis with Interbank deposit rates (measured in basis points) for currencies against USD (1-month available on request). The cross-

Table 1.H.4
LOOP violations for IBOR rates. 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad\qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
AUD	(i)	3.1	4.9	77	38	821	1.0	4.8	59	24	316
	(ii)	-4.9	4.9	12	0	821	-3.4	4.4	20	0	316
CAD	(i)	-19.9	6.2	0	0	800	-30.0	5.2	0	0	308
	(ii)	17.8	6.5	100	100	800	27.8	5.3	100	100	308
CHF	(i)	-16.4	17.6	0	0	821	-37.9	13.7	0	0	316
	(ii)	13.6	15.3	100	100	821	35.7	12.7	100	100	316
EUR	(i)	-15.2	9.3	1	0	818	-33.9	10.8	0	0	316
	(ii)	14.2	9.1	99	94	818	33.0	10.5	100	100	316
GBP	(i)	-2.3	4.2	10	2	821	-19.6	9.7	0	0	316
	(ii)	1.5	4.1	81	63	821	16.5	9.1	100	100	315
JPY	(i)	-17.0	14.0	0	0	821	-55.8	15.7	0	0	316
	(ii)	15.4	13.6	100	100	821	51.1	15.4	100	100	316

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for IBOR rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table 1.H.4
(Continued) LOOP violations with IBOR rates. 1-week and 1-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad\qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 1-month					
AUD	(i)	0.87	7.69	53	28	821	-5.4	9.2	30	0	316
	(ii)	-3.4	7.8	37	13	821	0.9	8.1	54	23	316
CAD	(i)	-25.8	9.9	0	0	800	-50.9	10.1	0	0	308
	(ii)	22.2	10.2	100	100	800	46.1	9.8	100	100	308
CHF	(i)	-16.6	25.7	0	0	821	-48.7	32.8	0	0	316
	(ii)	12.7	22.4	100	98	821	43.0	30.5	100	100	316
EUR	(i)	-14.7	12.3	3	0	818	-47.3	25.7	0	0	316
	(ii)	12.8	11.9	95	87	818	45.5	25.0	100	100	316
GBP	(i)	-6.9	6.5	0	0	821	-33.2	20.7	0	0	316
	(ii)	5.3	6.5	96	87	821	28.6	19.4	100	100	316
JPY	(i)	-19.2	20.9	0	0	821	-61.2	36.6	0	0	316
	(ii)	16.4	20.0	100	100	821	52.1	34.5	100	100	316
						B. 1-week					
CAD	(i)	-6.8	8.4	15	0	821	-16.9	16.4	5	0	316
	(ii)	0.6	7.6	53	12	821	4.8	14.2	71	24	316
CHF	(i)	-16.4	35.6	0	0	821	-38.8	62.9	0	0	316
	(ii)	9.1	23.3	85	58	821	20.9	51.9	99	95	316
EUR	(i)	-15.2	11.8	4	0	818	-33.6	55.8	0	0	316
	(ii)	10.3	10.3	92	60	818	27.5	47.9	100	100	316
GBP	(i)	-9.2	10.1	0	0	821	-24.3	42.5	0	0	316
	(ii)	5.2	9.5	87	73	821	15.2	37.6	92	64	316
JPY	(i)	-18.3	39.8	0	0	821	-49.3	72.2	1	0	316
	(ii)	10.6	27.9	98	82	821	23.3	57.7	93	50	315

Notes: The Table presents descriptive statistics for 1-week and 1-month LOOP deviations for IBOR rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table 1.H.4
(Continued) LOOP violations for interbank deposit rates. 1-week and 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
				Deviation					Deviation		
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 3-month					
AUD	(i)	-5.0	9.2	18	0	848	-28.5	20.7	13	0	326
	(ii)	3.2	9.2	70	12	848	26.2	20.2	83	48	326
CAD	(i)	-3.0	8.4	29	0	848	-28.8	22.3	18	0	326
	(ii)	0.6	8.7	54	2	848	26.4	22.3	81	49	326
CHF	(i)	-13.0	13.8	8	0	848	-46.7	19.5	0	0	326
	(ii)	9.8	13.0	88	37	848	44.3	20.0	99	87	326
EUR	(i)	-3.6	9.0	22	0	848	-30.8	19.2	6	0	326
	(ii)	2.6	8.9	71	7	848	29.7	19.2	94	74	326
GBP	(i)	-4.9	11.6	34	0	848	-31.0	18.9	7	0	326
	(ii)	3.9	11.4	62	7	848	28.4	19.2	90	59	325
JPY	(i)	-9.0	11.6	12	0	848	-36.7	20.6	5	0	326
	(ii)	7.7	11.6	81	26	848	34.4	21.8	84	57	326
						B. 1-week					
AUD	(i)	-7.7	15.3	10	0	848	-18.8	19.8	7	0	326
	(ii)	-0.1	13.7	50	1	848	3.6	16.2	60	0	326
CAD	(i)	-6.7	10.7	11	0	848	-31.1	27.3	3	0	326
	(ii)	0.2	9.7	52	2	848	20.3	28.4	86	21	326
CHF	(i)	-13.7	35.8	2	0	848	-35.8	63.7	6	0	326
	(ii)	5.0	27.1	72	12	848	17.6	55.1	82	38	326
EUR	(i)	-5.8	15.5	14	0	848	-32.0	63.9	0	0	326
	(ii)	1.2	13.3	61	6	848	22.3	55.6	97	63	326
GBP	(i)	-3.6	15.4	23	0	848	-26.7	51.6	2	0	326
	(ii)	-0.4	14.6	48	0	848	15.4	45.4	88	20	326
JPY	(i)	-11.7	39.2	5	0	848	-41.0	69.1	1	0	326
	(ii)	3.4	26.2	68	1	848	20.3	57.9	82	22	325

Notes: The Table presents descriptive statistics for 1-week and 3-month LOOP deviations for interbank deposit rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table 1.H.4
(Continued) LOOP violations for OIS rates. 1-week and 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
				Deviation					Deviation		
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 3-month					
AUD	(i)	9.1	9.4	71	61	847	2.6	9.2	67	53	325
	(ii)	-11.0	9.7	23	10	847	-4.9	7.8	28	18	325
CAD	(i)	-6.9	4.5	1	0	848	-17.0	9.6	0	0	325
	(ii)	4.4	4.7	91	63	848	14.1	9.6	100	100	325
CHF	(i)	-33.0	26.9	0	0	848	-88.8	19.6	0	0	325
	(ii)	30.3	24.8	100	100	848	85.3	19.2	100	100	325
EUR	(i)	-18.2	10.6	0	0	846	-59.3	17.6	0	0	325
	(ii)	17.3	10.4	99	95	846	58.1	17.4	100	100	325
GBP	(i)	-7.1	4.7	0	0	847	-33.3	12.7	0	0	325
	(ii)	6.2	4.6	100	98	847	28.7	12.4	100	100	324
JPY	(i)	-24.2	16.9	0	0	848	-79.9	24.2	0	0	325
	(ii)	22.8	16.3	100	100	848	75.8	24.2	100	100	325
						B. 1-week					
AUD	(i)	-1.5	13.3	45	5	847	-5.9	13.2	25	0	326
	(ii)	-6.5	13.7	27	6	847	-8.1	12.6	21	0	326
CAD	(i)	-9.7	8.3	7	0	848	-19.9	23.0	1	0	326
	(ii)	3.7	7.4	71	27	848	8.6	22.0	82	37	326
EUR	(i)	-17.7	14.5	2	0	848	-40.9	64.2	0	0	326
	(ii)	13.2	12.1	95	75	848	34.6	55.9	100	100	326
GBP	(i)	-8.1	13.3	0	0	848	-25.6	49.1	0	0	326
	(ii)	4.2	12.7	83	61	848	16.2	43.0	95	75	326
JPY	(i)	-21.5	46.2	0	0	848	-51.8	78.5	0	0	326
	(ii)	13.9	32.4	99	87	848	25.1	63.7	92	57	325

Notes: The Table presents descriptive statistics for 1-week and 3-month LOOP deviations for OIS rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table 1.H.5
LOOP violations for CP rates. 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} \quad - \quad \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad\qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} \quad - \quad \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Median	Std.	Deviation (%D)	(%M)	Obs
				A. 3-month		
(a) High-rated banks (A-1/P-1)						
EUR	(i)	-11.6	11.9	6	0	1,098
	(ii)	10.6	11.6	92	79	1,098
GBP	(i)	-4.1	9.1	9	0	1,099
	(ii)	3.2	8.3	81	51	1,098
JPY	(i)	-3.1	3.9	20	0	1,096
	(ii)	1.1	4.2	59	32	1,096
(b) Mid-rated banks (A-2/P-2)						
EUR	(i)	-7.2	10.1	6	0	1,099
	(ii)	6.1	9.8	90	63	1,099
GBP	(i)	-0.5	7.3	45	9	1,097
	(ii)	-0.4	6.6	47	19	1,096
JPY	(i)	-2.9	7.5	21	0	1,051
	(ii)	1.0	7.2	62	8	1,051

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel (a) shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel (b) reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table 1.H.5
(Continued) LOOP violations in CP rates. 1-month maturity

$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$

		Median	Std.	Deviation (%D)	(%M)	Obs
				B. 1-month		
(a) High-rated banks (A-1/P-1)						
EUR	(i)	-10.0	19.5	11	1	1,100
	(ii)	7.7	18.9	84	70	1,100
GBP	(i)	-3.4	14.2	8	0	1,100
	(ii)	1.6	13.3	69	37	1,100
JPY	(i)	-2.8	5.9	32	0	1,097
	(ii)	-1.6	7.9	42	21	1,097
(b) Mid-rated banks (A-2/P-2)						
EUR	(i)	-7.3	17.7	8	0	1,096
	(ii)	5.4	17.1	85	52	1,096
GBP	(i)	-2.0	17.1	28	0	1,100
	(ii)	-0.1	16.0	50	25	1,100
JPY	(i)	-3.5	16.9	27	3	1,042
	(ii)	0.5	15.2	53	6	1,042

Notes: The Table presents descriptive statistics for 1-month LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel (a) shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel (b) reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table 1.H.5
(Continued) LOOP violations for CP rates. 1-week maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Median	Std.	Deviation (%D)	(%M)	Obs
				C. 1-week		
(a) High-rated banks (A-1/P-1)						
EUR	(i)	-6.9	20.0	17	3	949
	(ii)	1.8	16.2	60	27	949
GBP	(i)	-2.8	11.7	19	1	912
	(ii)	-1.4	10.3	31	2	912
JPY	(i)	-1.8	51.1	33	0	895
	(ii)	-8.1	54.5	16	4	895
(b) Mid-rated banks (A-2/P-2)						
EUR	(i)	-9.5	30.5	10	0	1,061
	(ii)	3.7	25.4	68	30	1,061
GBP	(i)	-4.1	21.3	23	0	1,087
	(ii)	-1.5	18.3	38	11	1,087
JPY	(i)	-4.8	8.4	25	0	365
	(ii)	-1.7	8.7	40	12	365

Notes: The Table presents descriptive statistics for 1-week LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel (a) shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel (b) reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table 1.H.6
Risk-free CIP arbitrage funded via the CP market and invested in CB deposits. 1-week and 1-month maturity

	1-month					1-week				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
I: Post-crisis to beginning MMF reform period (Jan 2013 – Mar 2016)										
A. Mid-rated banks (A-2/P-2)										
AUD	**-42.3**	10.1	0	0	702	**-38.8**	11.7	0	0	698
CAD	**-7.2**	7.3	16	3	784	**-3.4**	7.4	31	1	778
CHF	**8.9**	24.3	98	82	784	**7.2**	21.9	82	50	778
EUR	**-9.1**	14.6	19	16	781	**-5.1**	11.9	26	5	775
GBP	**0.2**	7.5	51	22	783	**3.4**	9.3	72	40	777
JPY	**13.0**	20.8	95	82	782	**9.2**	27.5	94	62	776
B. High-rated banks (A-1/P-1)										
AUD	**-34.6**	8.7	0	0	702	**-31.7**	10.0	0	0	694
CAD	**1.3**	6.9	59	26	784	**3.2**	8.1	68	26	776
CHF	**16.6**	24.8	100	97	784	**13.2**	23.6	94	75	776
EUR	**1.3**	15.3	52	46	781	**0.8**	13.5	53	37	773
GBP	**8.7**	6.0	100	100	783	**10.9**	10.5	92	83	775
JPY	**20.2**	21.3	100	100	782	**16.3**	29.6	100	95	774

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the post-crisis period prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). The crucial aspect for a proper arbitrage, seen from the arbitrageur's perspective, is that the investment is risk-free, here represented by investing in central bank deposits. Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits, and proportion of days (%D) and months (%M) during the sample when a positive arbitrage profit is observed.

Table 1.H.6
(Continued) Risk-free CIP arbitrage funded via the CP market and invested in CB deposits. The MMF reform sample. 1-week and 1-month maturity

	1-month					1-week				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
	II: MMF reform sample (Apr 2016 – June 2017)									
	A. Mid-rated banks (A-2/P-2)									
AUD	**-45.3**	10.4	0	0	294	**-45.2**	17.7	0	0	293
CAD	**-3.4**	10.8	38	0	316	**-4.6**	18.9	36	0	314
CHF	**36.0**	29.0	100	100	316	**16.7**	46.6	97	71	314
EUR	**30.3**	23.0	100	94	316	**14.9**	42.0	99	80	314
GBP	**16.5**	17.9	96	69	316	**7.1**	31.4	83	34	314
JPY	**34.1**	34.1	100	93	307	**7.5**	50.5	70	12	305
	B. High-rated banks (A-1/P-1)									
AUD	**-32.4**	7.6	0	0	294	**-31.0**	11.3	1	0	254
CAD	**6.7**	9.7	88	50	316	**9.6**	15.2	81	38	276
CHF	**48.5**	31.7	100	100	316	**30.2**	55.5	100	100	276
EUR	**43.3**	25.2	100	100	316	**28.8**	50.3	100	100	276
GBP	**28.8**	19.5	100	100	316	**19.4**	39.7	98	80	276
JPY	**47.0**	36.5	100	100	307	**23.0**	60.8	88	37	267

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the post-crisis period prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). The crucial aspect for a proper arbitrage, seen from the arbitrageur's perspective, is that the investment is risk-free, here represented by investing in central bank deposits. Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits, and proportion of days (%D) and months (%M) during the sample when a positive arbitrage profit is observed.

Table 1.H.7
CIP arbitrage and FX swap market order flow imbalances across maturities

	3-month		1-month		1-week	
	A-2/P-2 (1)	A-1/P-1 (2)	A-2/P-2 (3)	A-1/P-1 (4)	A-2/P-2 (5)	A-1/P-1 (6)
Constant	-0.936	0.159	0.475	0.371	1.228	1.953
	(-2.02)	(0.77)	(0.90)	(0.74)	(1.13)	(1.38)
Error correction	-0.100	-0.020	-0.033	-0.015	-0.095	-0.037
	(-2.80)	(-1.41)	(-1.27)	(-1.20)	(-2.06)	(-0.52)
Swap OF, in arb.	0.374	0.531	1.239	1.280	3.479	3.129
	(1.65)	(4.81)	(4.49)	(5.40)	(3.22)	(2.62)
Swap OF, no arb.	0.330	0.319	0.180	0.438	0.441	1.153
	(2.35)	(2.38)	(0.65)	(1.64)	(0.99)	(1.53)
Dollar index, in arb.	0.001	0.005	0.004	0.017	0.057	0.059
	(0.06)	(0.87)	(0.16)	(1.54)	(1.62)	(1.73)
Dollar index, no arb.	-0.002	0.005	-0.024	0.008	0.007	0.003
	(-0.20)	(0.85)	(-1.46)	(0.86)	(0.48)	(0.16)
Lagged ΔCIP	-0.163	-0.048	-0.196	-0.009	0.025	0.045
	(-1.49)	(-1.34)	(-3.39)	(-0.17)	(0.42)	(0.68)
Obs.	924	924	924	924	907	702
adj.R^2	0.08	0.04	0.08	0.02	0.02	0.01

Notes: The Table shows results from panel-regressions for changes in CIP deviations, measured in basis points, across six different currencies. CIP deviations are based on funding in the U.S. CP market for banks with either A-2/P-2 rating or high-rated banks with A-1/P-1-rating, and invested in central bank deposits. The constant (not reported) and error-correction term (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on whether a deviation exists. The return on FX spot is measured in basis points, while swap order flows are standardized by own standard deviation. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: April 2016 – June 2017.

Chapter 2

Price-setting in the FX swap market

2.1 Introduction

Foreign Exchange (FX) swaps allow market participants to hedge exchange rate risk arising from currency mismatch between assets and liabilities. After growing steadily over the past decade, FX swaps are now the most traded foreign exchange instrument worldwide, with a daily turnover of approximately $3.2 Trillion USD (2019 BIS triennial survey). In theory, the pricing of FX swaps is pinned down by Covered Interest Parity (CIP) - a renowned no-arbitrage relationship in international finance. CIP states that the rate of return on equivalent domestic and foreign assets should equalize after covering exchange rate fluctuations in the FX swap market. However, the FX swap market has been subject to considerable scrutiny since the global financial crisis, as the pricing no longer obeys the iron law of CIP. Since 2008, CIP deviations have been large and persistent, and have implied a systematic premium to swap EUR, CHF and JPY into USD via FX swaps (Figure 2.1). In this paper we focus on the mechanisms that govern price-setting in the FX swap market.

While much of the recent literature focuses on why CIP deviations exist, and range from explanations that center on limits to the supply of dollars in the FX swap market due to bank regulations (Du et al., 2019; Cenedese et al., 2019; Bräuning and Puria, 2017a) and funding constraints (Rime et al., 2019a; Liao, 2020), as well as factors that lead to an excess demand for dollars in the FX swap market (Borio et al., 2016b; Sushko et al., 2016), less is understood about the role of price-setting in the FX swap market. This paper aims to fill this gap. To this end, we examine order flow - the net of buyer and seller initiated transactions - as a fundamental signal used by dealers to update the forward rate of the FX swap contract. In particular, we investigate the price impact of order flow before and after the financial crisis and how dealers respond to different types of information.

When a no-arbitrage relationship like CIP holds tightly, the role of order flow is confined to correcting short-lived periods of mispricing. In the pre-crisis period, money markets were characterized by low heterogeneity in funding costs where Libor (London interbank offered rate) acted as an accurate representation of banks' marginal cost across currencies. This made price-setting in the FX swap market a straightforward process, where the dealer takes interest rates in respective currencies as given. The dealer then sets the forward rate according to CIP so that the returns are equalized after covering the exchange rate risk. Hence, we hypothesize that the price impact of order flow is small prior to 2008. In contrast, the post-crisis period is characterized by a large dispersion in funding costs, differences in funding availability across currency areas and tighter constraints on banks' balance sheets. This makes it difficult for dealers to determine the equilibrium price. We hypothesize that dealers use order flow in the post-crisis period as a signal to set the forward rate. By exploiting time variation in the dispersion of funding costs and balance sheet constraints we examine how these factors can account for an increase in the price impact of order flow.

Our order flow measure is based on transaction level data from the Thomson Reuters D2000-2 platform. This platform registers inter-dealer transactions in the FX swap market where each trade is signed as either a buyer or a seller initiated transaction. The daily net of buyer and seller initiated transactions constitutes our order flow measure. In our sign convention, we interpret a positive order flow as net buying pressure to obtain USD through FX swaps. Due to superior market depth, we use 1-week maturity as our preferred tenor and base our empirical analysis on the 1-week FX swap order flow and 1-week deviation from CIP.[1]

We start by developing a microstructural model of the FX swap market. The model has three key agents; customers, arbitrageurs and dealers. Customers are managing the currency exposure on their balance sheets, for example by swapping foreign currency into USD. Arbitrageurs provide funds through the FX swap market when arbitrage opportunities appear. Dealers act as intermediaries and match the flows of customers and arbitrageurs and typically try to keep their positions flat to avoid financing inventories (Lyons, 1995a; Bjønnes and Rime, 2005). Dealer aversion to inventory accumulation yields a price-setting condition in which the forward rate is set to correct order imbalances. The model's primary contribution is to map a linear relationship between order flow and the price-setting of FX swaps. We can use this framework to study how the price impact of order flow is governed by shocks to arbitrageurs. For example, the model predicts that a tightening of funding and balance sheet constraints leads to an inelastic supply of arbitrage capital, with dealers adjusting the price substantially to avoid order flow and balance inventories.

Guided by our model, we first estimate the price impact of order flow, and find it has increased substantially after the global financial crisis in 2008. Since the crisis, a positive 1 standard deviation shock to order flow, i.e. demand to borrow USD through the FX swap market, causes a widening of CIP deviations by up to 4 basis points. That is, when the demand for USD in the FX swap market increases, the cost of obtaining dollars through FX swaps increases as well. We then test why the price impact of order flow is a post-crisis phenomenon by examining potential differences in the price impact of order flow in periods when the heterogeneity in US funding costs is large and when balance sheet expansion is particularly costly for banks.[2] Our estimates reveal that up to three quarters of the increased price impact can be attributed to periods when funding heterogeneity in USD is high and when the FX swap contract crosses regulatory reporting dates at quarter-ends. Higher funding heterogeneity reduces the number of potential arbitrageurs as an increasing share of market participants face funding costs exceeding the threshold necessary to reap arbitrage profit. Similarly, regulatory reporting at quarter-ends give arbitrageurs incentives to reduce their provision of arbitrage capital. Consequently, a larger price adjustment is necessary for dealers to balance inventories.

In addition to the time varying price impact of order flow, we also test whether news is impounded in the price contemporaneously, or through trading (see Evans and Lyons (2005) for analysis on the FX spot market). Our model predicts that *private* information is revealed through order flow

[1] Note that our aim is not to precisely measure CIP arbitrage opportunities, but rather price-setting in the FX swap market. We are therefore using 1-week Libor rates as the benchmark rate in our CIP calculation. Importantly, by examining CIP deviations instead of the forward rate directly, we control for movements in the forward rate that relates to changes in the interest rate differential.

[2] We define periods of funding heterogeneity by the daily cross sectional dispersion in 3-month US Libor panel quotes.

meaning that prices adjust as a result of trading activity. For example, suppose in response to a shock to its access to dollar funding, a Euro area bank now obtains dollars via the FX swap market. If the bank's information is private and not known to the dealers before the order appears, these excess demands translate to order flow in the inter-dealer market, which can then be used by dealers to update the forward rate. Alternatively, we hypothesize *public* information is impounded in the price contemporaneously. For example, consider a scheduled monetary announcement of a central bank, where the outcomes of the meeting are conveyed to all market participants simultaneously. If the announcement implies a change in the interest rate differential between two currencies, the dealer can reset the forward rate to match the change in the interest differential. In this setting, the monetary news is impounded in the price, suggestive of efficient price-setting in the FX swap market.

We test whether the public or private information view is relevant in price-setting by studying three different types of events. First, we examine the effect of Federal Reserve Swap lines during the period 2007-2010. The swap lines allowed foreign central banks to provide US dollar funding directly to their own eligible counterparties. By doing so, a larger set of counterparties were able to access USD directly from the central bank rather than via the FX swap market.[3] Although it is publicly announced when these auctions take place, the dealers do not have detailed information on whether individual counterparties would draw on the swap line.[4] Therefore, we expect swap lines will reduce the demand for USD through FX swaps and lower the order flow into USD. Second, we look at dates when the FX swap contract crosses quarter-ends. A large number of banks report quarter-end balance sheet snapshots to regulators. This implies incentives to reduce the size of the balance sheet leading to a more inelastic supply of arbitrage capital and significant price effects over reporting dates, as documented in Du et al. (2019). Given quarter-ends are public information and known to dealers in advance, we hypothesize contemporaneous price adjustment. Third, we identify monetary policy surprises to test whether the adjustment in the forward rate following monetary policy announcements happens through order flow. Following our example of a monetary announcement constituting public information, our theory points towards monetary news being impounded in the forward rate contemporaneously.

Turning to the empirical evidence, we find evidence that the swap lines reduced the order flow into USD which in turn affected the forward rate, supporting the private information hypothesis. In response to quarter-ends, we utilize high frequency data of forward rates to show a large contemporaneous price adjustment exactly at the hour the FX swap contract crosses quarter-ends, with the

[3] Alternatively, the swap line also relaxes arbitrageur balance sheet constraints and increases arbitrageurs' ability to supply dollars in the FX swap market. The effects on both customers and dealers will have an equivalent effect of reducing the relative demand for dollar funding in the FX swap market.

[4] We stress that the private information is not the announcement of the swap line itself, which is known to dealers, but the details of counterparties that use the swap line. For example, only a subset of banks that draw on the swap line may have previously been relying on dollar funding via FX swaps. Similarly, banks may now start using these dollar funds to supply dollars in the FX swap market. Both of these outcomes are unanticipated by dealers until they are revealed as positive order flow.

full price adjustment priced within two hours. Finally, in line with the hypothesis of public information we find no effect on order flow of monetary policy announcements. These results highlight that dealers efficiently adjust the price according to publicly available information.

Roadmap. The paper is outlined as follows. Section 2.2 provides an overview of related literature. In section 2.3, we outline definitions of covered interest rate parity, FX swaps and order flow and describe the data. In section 2.4, we develop a model of the microstructure of the FX swap market and derive a price-setting rule that relates the forward rate of the swap to order flow observed in the inter-dealer market. In section 2.5, we first provide baseline estimates of the price impact of order flow. In section 2.6, we empirically test the microstructure hypotheses of how prices are determined in response to public and private sources of information, using the response of the FX swap market in response to quarter-end bank regulations and central bank swap lines. In section 2.7 we conclude.

2.2 Related literature

The literature on post 2008 CIP violations naturally centre on theories of what are the supply and demand fundamentals in the FX swap market that explain persistent violation of deviations. Theories on limits to the supply of dollars in the FX swap market include rising balance sheet costs and regulatory requirements (Du et al., 2019; Liao, 2020; Bräuning and Puria, 2017a), the role of the dollar in constraining leverage (Avdjiev et al., 2019), and rising bid/ask spreads due to limited dealer capacity (Pinnington and Shamloo, 2016), costs to leverage such as shareholder risk (Andersen et al., 2019) and rising counterparty or liquidity risk (Baba and Packer, 2009a; Griffoli and Ranaldo, 2010). Other factors affecting agents demands for dollars in the FX swap market include declines in bank quality, declines in short-term funding, unconventional monetary policies, and central bank swap lines (Sushko et al., 2016; Bahaj et al., 2018b; Ivashina et al., 2015; Iida et al., 2016). This paper contributes to understanding CIP violations by understanding how constraints on the supply of dollars in the FX swap market can lead to price discovery through order flow. This is a critical component of the FX swap market microstructure and we show empirically that dealers use order flow as a fundamental signal to update the forward rate of the FX swap.

The seminal work on market microstructure in FX has typically examined the price impact of order flow on spot foreign exchange markets (Evans and Lyons, 2002, 2005, 2006; Berger et al., 2008; Rime et al., 2010; Ranaldo and Somogyi, 2019). Microstructure models in Evans and Lyons (2002) have typically used simultaneous trade models in which dealers set prices, and use inter-dealer order flow following a trading round as information to reset prices. In developing our model framework of the FX swap market, we share many of the elements in trading, however we note two clear differences in FX swaps. The first is that customers in the FX swap market are trading for hedging purposes. In contrast, investors in the FX spot market are composed of informed and uninformed traders, with informed traders having an information advantage in the price of the spot exchange rate, which is treated as a speculative asset. Second, we add arbitrageurs to the framework as they attempt to make systematic profits from the mispricing of the forward rate. Using our framework, we derive a price-setting relation in which price adjustment of the FX swap, which we denote by the change in the CIP deviation, is linearly related to order flow.

Finally, we relate to a recent interest in understanding the microstructure and impact of order flow in the FX swap market. Krohn and Sushko (2017) examine how the market structure of the FX swap market has led to a reduction in market liquidity and rising bid/ask spreads during quarter-end periods. Cenedese et al. (2019) and Rime et al. (2019a) find evidence that order flow has price impact in the post-crisis period. We extend their work in several ways. First, our measure of order flow is based on each trade being marked as buyer or seller initiated within the data from the trading platform, not the Ready-Lee algorithm. This eliminates potential errors and enable us to sign each trade. Second, through a model framework, we derive the price impact of order flow on the FX swap market through an inter-dealer market that sets the forward rate to minimize inventory accumulation. Third, in contrast to the existing literature we provide an explanation on how price impact of order flow has changed after the financial crisis. Our model framework enables us to link two factors, increased dispersion in dollar funding costs, and the tightening of leverage constraints, that explain up to three quarters of increased price impact we observe empirically in the post-crisis period. Fourth, we find that the source of information matters: in response to public announcements, dealers set the forward rate contemporaneously. In contrast, order flow plays a significant role in price-setting of the forward rate in response to private information, and this is substantiated through the allotment of central bank swap lines by the Federal Reserve in the period 2008-2010.

2.3 Definitions and data

Definitions

Foreign exchange swaps

Foreign exchange swaps, also known as spot-forward contracts, are used by banks and corporates to hedge balance sheet risk. A bank may hedge the FX exposure due to a mismatch of their currency assets or liabilities, with evidence in Borio et al. (2016a) that Japanese banks have significantly higher dollar assets than liabilities, causing them to turn to the FX swap market for dollar funding. [5] We illustrate the legs of a EUR/USD FX swap in Figure 2.2. In the first leg of the contract, the customer exchanges a principal of X EUR at the current spot rate S USD per EUR. The customer receives SX USD. Both parties then agree to re-exchange the principals at maturity at a specified

[5] Similarly, a corporate may hedge the currency mismatch of their cash flows, for example if a European corporate has profits in USD from their offshore activities, they will hedge the foreign exchange risk by swapping their USD receivables with EUR.

forward rate, this is known as the forward leg of the contract. The customer receives their X EUR, and the dealer then receives FX USD, where F is the forward rate of the contract.

In the empirical analysis the focus is on short-term FX swaps with maturity of 1-week. We focus on this maturity because the majority of platform trading in FX swaps happens at short maturities. At longer maturities, the use of brokers and telephone-based trading are more common.

Covered Interest Rate Parity

Covered interest rate parity (CIP) states that two assets with identical characteristics in terms of credit risk and maturity, but denominated in different currencies, have the same rate of return after accounting for exchange rate risk using a forward contract. To illustrate, let us consider an investor that can borrow at the risk-free rate in USD or EUR. The total cost of borrowing 1 USD directly is $1 + r^f_\$$. Alternatively, the investor can borrow USD via the FX swap market. To do so, they borrow $\frac{1}{S}$ EUR, where S is the quotation in USD per EUR. The total cost in EUR is then $\frac{1+r^f_d}{S}$. They exchange the EUR into USD and hedge the exchange rate risk with a forward contract, which gives a synthetic dollar cost of $\frac{F}{S}(1 + r^f_d)$. The CIP deviation is defined as the difference between the direct and synthetic dollar borrowing cost, which we formally state in equation 2.1.

$$\Delta = \underbrace{1 + r^f_\$}_{\text{direct}} - \underbrace{\frac{F}{S}(1 + r^f_d)}_{\text{synthetic}} \tag{2.1}$$

Since 2008, the cost of borrowing USD through the FX swap market - the synthetic interest rate in USD - based on EUR, CHF and JPY has been higher than the corresponding direct funding cost in USD. The CIP deviations can therefore be interpreted as a synthetic dollar borrowing premium. We document this in Figure 2.1, which plots 1 year CIP deviations for the EUR/USD, CHF/USD and JPY/USD pairs.

In this paper, when we refer to price-setting of the FX swap, we specifically refer to a dealer setting the forward rate, taking interest rates and the spot rate as inputs. We make this distinction in equation 2.2, where in the pre-crisis period, deviations were rather small, $\Delta_{pre-crisis} \approx 0$, and so the forward rate is set by dealers consistent with CIP arbitrage (Akram et al., 2008).

$$\Delta_{pre-crisis} \approx 0 \implies F = S\frac{1 + r^f_\$}{1 + r^f_d} \tag{2.2}$$

In the post-crisis period, significant deviations from parity suggest dealers set the forward rate in response to underlying demand and supply fundamentals in the FX swap market. Price determination is complicated by heterogeneity in funding spreads, leverage constraints and customer quality during this period. As we will outline in our microstructural model of the FX swap market, these factors can cause an inelastic supply of arbitrage capital, increasing the price impact of order flow.

Data

CIP deviations

To compute CIP deviations at the 1 week maturity, we use Thomson Reuters tick history which contains historical data on spot and 1 week forward rates of the EUR/USD, CHF/USD and JPY/USD pairs measure at 6 PM Central European Time. Swap points, also referred to as pips, are used to get the forward exchange rate, $F = S + \frac{sp}{10^4}$, where we express S and F as dollars per unit of domestic currency, and so the dollar is classified as the quoting currency. The CIP deviation we calculate in equation 2.3 is expressed as the difference between the local dollar borrowing rate less the synthetic dollar borrowing rate, where i_q is the US interest rate, i_b is the base interest rate (denominated in EUR, CHF or JPY), S is the spot rate and F is the forward rate, calculated as the mid-point using bid and ask quotes.[6] A negative Δ indicates that synthetic dollar borrowing costs exceed local borrowing costs, and this is indeed the case for the EUR/USD, CHF/USD and JPY/USD pairs. For a measure of risk-free rates, we use the 1 week Libor in the quoting and base currencies. In constructing the CIP deviation, we convert our forward premium $\frac{F}{S}$ to annualised percentage points in order to construct a measure of 1 week CIP deviations in annualised terms.[7]

$$\Delta_t = 1 + i_{q,t} - \frac{F_t}{S_t}(1 + i_{b,t}) \tag{2.3}$$

Summary statistics for the three currency pairs are provided in Table 2.1, for the EUR/USD, CHF/USD and JPY/USD pairs respectively. CIP deviations are much wider in the post 2008 period, with an average of 30 basis points for all pairs. Average deviations are negative, suggesting that the US Libor rate is less than a synthetic Libor rate based on borrowing in EUR, CHF or JPY and swapping into USD using a forward contract. The range of CIP deviations also increases significantly with measured spikes of up to -300 basis points. These spikes correspond to quarter-end periods, which we investigate empirically in following sections.

Order Flow

Order flow is defined as the net of buyer initiated transactions. We define a transaction as buyer initiated if it is initiated by a counterparty swapping EUR, CHF or JPY into USD. Conversely, a transaction is seller initiated if the transaction is swapping USD into foreign currency. To measure order flow at short-term maturities, we use the Reuters D2000-2 trading platform, which contains inter-dealer trades from January 1st 2005 to September 1st 2017 in FX swaps for the EUR/USD, CHF/USD and JPY/USD pairs. We use the 1 Week maturity as it is the most liquid and traded pair at maturities above 1-day. The dataset has quotes in the inter-dealer market, with columns indicating bid price, ask price, a timestamp of the quote to the nearest second, and a column for the

[6] To calculate the mid spot rate, we average the spot rates at ask and bid, $S = \frac{S_a + S_b}{2}$. Similarly, the forward rate is calculated as the mid point of bid and ask quotes, $F = \frac{F_a + F_b}{2}$

[7] We account for the exact number of trading days by properly adjusting for bank holidays in the respective currency pairs

market price when a trade has occurred. Additionally, our data set has a column indicating if the trade was buyer or seller initiated. Using this data, we can construct a measure of order flow. The measure of order flow is then given as the net of buyer initiated transactions, where buyer initiated transactions are signed +1 and seller initiated transactions are signed -1. The order flow for 1 week FX swaps are measured in counts as we do not have trade volume in the TR D2000-2 database. [8]

$$OF_t^{count} = \sum_{k=t_0}^{k=t} 1[T_k = B] - 1[T_k = S]$$

Summary statistics of order flow using the inter-dealer trades are provided in Table 2.2. The mean of net buyer initiated trades is close to zero, and the standard deviation of trades ranges from 2-5 net buyer transactions per day. The EUR/USD pair has the highest range of order flow, with a range of [-30,+30]. We provide plots of daily order flow in Figure 2.3.

Funding dispersion

We calculate the daily dispersion in the 3-month Libor contributions as a proxy for funding heterogeneity. The measure is computed as the difference between the highest and lowest daily submission by the contributing panel banks. A higher value indicates larger dispersion in funding costs among the panel banks. Data until February 1st 2014 for individual Libor submissions can be obtained from Bloomberg. After this date Intercontinental Exchange (ICE) took over as Libor administrator from British Bankers Association (BBA) and the data can be obtained from ICE. Figure 2.4 shows the dispersion in 3-month Libor during our sample period ranging from January 1st 2005 to September 1st 2017.

Bid/ask spreads and price volatility

In the empirical part of the paper we also exploit the high frequency data from the Thomson Reuters tick history to create bid/ask spreads and a measure of intra-day price volatility. The measure of bid/ask spreads is the daily average of the last observation each hour. Figure 2.5 shows the evolution of the bid/ask spreads during the sample period. As a measure of daily price volatility, we compute the daily standard deviation based on hourly observations. The intra-day price volatility is depicted in Figure 2.6.

2.4 Model

Before turning to the empirical results, we first develop a model to structure our testable hypotheses. As a starting point, we introduce three types of agents in the model, customers, arbitrageurs, and dealers. Customers include banks, other financial institutions and non-financial institutions that

[8] Note that the common way of measuring order flow is to follow the algorithm provided in Lee and Ready (1991), which sign transactions as buyer or seller initiated based on bid and ask quotes. In our data we know the direction of the trade (seller or buyer initiated) is already indicated. This means that we are able to sign all trades correctly.

manage currency mismatch between assets and liabilities by hedging their positions via FX swaps. In addition to customers, there are a distinct group of arbitrageurs. The arbitrageurs can step in and supply funds in the FX swap market to earn arbitrage profits from mispricing of the forward rate in response to underlying demand from customer flows. The third group of agents are dealers, who set the forward rate of the FX swap. The objective of dealers is to match flows as much as possible, both from customers and arbitrageurs. Any unmatched flows are submitted to the inter-dealer market and are observed as order flow. The key assumption in price-setting is that the inter-dealer market sets the forward rate to avoid order imbalances.

The primary contribution of the model is in deriving a relationship between order flow and price-setting of the forward rate. Additional testable implications include an analysis of the factors that affect price impact. We identify two factors, shocks to arbitrageur capital in the form of heterogeneous funding costs and leverage constraints, increase the price impact of order flow.

Arbitrageurs

Following Sushko et al. (2016), we model an arbitrageur that has expected exponential utility over next period wealth W_{t+1}. Formally, we define $U_t = E_t\left[-e^{-\rho W_{t+}}\right]$, where ρ is a measure of risk aversion. The arbitrageur decides to lend $x_{\$,j,t}$ dollars in the FX swap market. To do so, they first borrow at the dollar risk-free rate $r^f_{\$}$. The dealer exchanges principals at a specified spot exchange rate s_t dollars per unit of domestic currency, with an agreement to re-exchange principals at maturity at the forward rate f_t. During the contract, they invest the domestic currency, at a risk-free rate r^f_d. The CIP deviation, Δ_t, is the excess of the forward premium over the interest rate differential, $\Delta_t = f_t - s_t - (r^f_{\$} - r^f_d)$.[9] In our model, the arbitrageur faces three limits to arbitrage: counterparty risk, funding costs, and leverage constraints. We detail each of these channels below.

Counterparty risk

The arbitrageur bears counterparty risk. In the event of a default with a given probability θ, the arbitrageur does not earn the forward premium $f_t - s_t$ on the trade, but instead earns a stochastic return based on the realized spot rate exchange rate s_{t+1}.[10]

Funding costs

Funding spread heterogeneity is a post-crisis feature and is typically represented as higher credit spreads in dollars, as well as more dispersion in Libor rates for banks (Rime et al., 2019a). The

[9] Note that the definition of the CIP deviation in the model is the negative of the CIP deviation expressed in the empirical evidence. We change the notation for the model as we are taking the perspective of an arbitrageur supplying dollars in the FX swap market.

[10] Our model excludes the market practice of paying margin in FX swaps. This would imply that moves in the underlying spot exchange rate are effectively collateralized by the counterparty. An implication of the margining practice is that the arbitrageur faces liquidity risk instead. However, in short-term FX swaps, the liquidity risk connected to margining is limited. Similarly, an arbitrageur may minimise counterparty risk by conducting the trade with its own dealer, if it is an arm of an investment bank. Therefore, we do not consider counterparty risk as a relevant factor in our empirical analysis.

dollar funding spread reflects individual arbitrageur funding margins over the risk-free rate.[11] We model this formally, with each arbitrageur j facing a marginal funding cost $c_{\$,j,t}$ over the risk-free rate $r^f_\$$.

Leverage constraints

As the ratio of debt to total assets increases with more arbitrage capital, so does the marginal cost of obtaining dollars. For example, in Bräuning and Puria (2017b) they find evidence that the size of the swap position leads to higher forward premiums charged by dealers, all else equal. This is especially heightened in quarter-end periods when leverage constraints prevent agents from borrowing dollars for arbitrage capital (Du et al., 2019; Cenedese et al., 2019).We capture costs to arbitrageur leverage, $\phi_t\left(\frac{x}{W}\right)$, with $\phi_t(.) > 0$. This is a stylized way of capturing regulatory factors such as requirements on a minimum level of risk-weighted capital to assets, and other costs of scaling the balance sheet to conduct CIP arbitrage.

We can write the evolution of wealth in the next period as the sum of returns on initial wealth, CIP arbitrage profits and the difference between the actual spot rate at t+1 and the forward rate.

$$W_{t+1} = \underbrace{W_t(1+r^f_\$)}_{\text{return on wealth}} + \underbrace{x_{\$,j,t}\Delta_t}_{\text{cip arbitrage}} + \underbrace{\theta x_{\$,j,t}(s_{t+1}-f_t)}_{\text{counterparty risk}} - \underbrace{x_{\$,j,t}(c_{\$,j,t})}_{\text{funding spreads}} - \underbrace{W_t\phi_t\left(\frac{x_{\$,j,t}}{W_t}\right)}_{\text{leverage constraint}} \tag{2.4}$$

Assuming $s_{t+1} \sim N(f_t, \sigma^2)$, and drawing on the properties of the exponential distribution, maximizing the log of expected utility is equivalent to mean-variance preferences over wealth.

$$\max_{x^*_{\$,j,t}} \rho\left(W_t(1+r^f_\$) + x_{\$,j,t}\Delta_t - x_{\$,j,t}(c_{\$,j,t}) - \frac{1}{2}\rho\theta^2 x^2_{\$,j,t}\sigma^2 - W_t\phi_t\left(\frac{x_{\$,j,t}}{W_t}\right)\right) \tag{2.5}$$

The equation for the supply of dollars by the arbitrageur takes the following piece-wise functional form, provided in equation 2.6. An arbitrageur will only supply dollars if their funding cost is below a threshold $c^*_\$$. We define the funding cost threshold as the point at which the net arbitrage profits *ex ante*, $\Delta - c^*_\$ - \phi'_j\left(\frac{x_{\$,j,t}}{W_t}\right) = 0$. The optimal supply of dollars by an arbitrageur is given by $x_{\$,j,t}$.

$$x^*_{\$,j,t} = \begin{cases} \frac{\Delta_t - c_{\$,j,t} - \phi'_j\left(\frac{x_{\$,j,t}}{W_t}\right)}{\rho\theta^2\sigma^2} & , c_{\$,j,t} < c^*_\$ \\ 0 & , c_{\$,j,t} \geq c^*_\$ \end{cases} \tag{2.6}$$

To summarize, arbitrageur supply of dollars is positively related to the forward premium (and CIP deviation Δ), and negatively related to dollar funding spreads and leverage constraints. Increased heterogeneity in dealer funding spreads, for example, will cause more arbitrageurs to have too high

[11] Note that we are using the Libor fixing as a proxy for the risk-free rate in the empirical part of the paper. This is strictly speaking not accurate, but our mission in this paper is to investigate the price-setting in FX swaps, not to precisely measure arbitrage opportunities.

funding spreads $c_{\$,j,t} \geq c^*_{\$}$, and to not supply dollars in the FX swap market. We will discuss the implications of funding spread heterogeneity for price-setting in the inter-dealer market in a following section.

Customers

Customers, typically banks, use the FX swap market to hedge their currency balance sheet mismatch. We capture customer demands by the following stylized function, where banks are in a continuum [0,1] indexed by bank quality θ_b and the CIP deviation Δ. Importantly, $x^D_{\$,t}$ is a measure of the net demand for USD at the spot leg of the FX swap.

$$x^D_{\$,t} = \int_0^1 f(\theta_b, \Delta) db \tag{2.7}$$

The first determinant of net demand for USD in the FX swap market is θ_b, which measures counterparty quality. All else equal, counterparties with higher quality are more likely to obtain dollars directly via commercial paper markets or bank deposits. Therefore, demands for dollar funding via FX swaps is inversely related to counterparty quality. The increase in counterparty risk is a key determinant of the increased demand for dollar constrained banks in the FX swap market in 2008 (Baba and Packer, 2009a). The second determinant of net demand is the CIP deviation Δ. All else equal, a higher CIP deviation implies an increase in the net cost of swapping euros, swiss francs and yen into dollars. Evidence in Eguren Martin et al. (2018) suggests that in response to shocks to the CIP deviation, banks' net demand for dollars in the FX swap market declines.

Inter-Dealer Market

We have defined customers and arbitrageurs. Each of these agents are price-takers, and go to a market-maker to find a counter-party to take the other side of the trade. The market-maker is the dealer in our model. The dealer's objective is to match flows of swapping domestic currency into dollars with opposing flows. This is consistent with theories of market microstructure where dealers are sufficiently risk averse to holding inventory (see Lyons (1995b) and Bjønnes and Rime (2005) for empirical evidence on dealers minimizing inventory). Moreover, all dealers in FX swaps are associated with a bank. Therefore, the dealer faces the same funding costs and constraints as the mother bank that indeed can be part of the group of arbitrageurs. We denote the net dollar demands by customers to dealer j by $x^D_{\$,j}$. Denote the net supply of dollars by arbitrageurs to dealer j by $x^*_{\$,t,j}$. Unmatched flows in dollars are submitted to the inter-dealer market. We illustrate the unmatched flows of a dealer in Figure 2.7. The dealer submits the excess demand for dollar funding to the inter-dealer market, and this is observed as $OF_{t,j}$ in the Figure.

Aggregating across all dealers, we obtain an expression for inter-dealer order flow OF_t, in equation 2.8. Inter-dealer order flow is equal to the net buying pressure of swapping EUR, CHF or JPY (domestic currency) into USD. Net customer demands for USD at the spot leg of the FX swap is equal to $x^D_{\$,t}$. Net supply of dollars by N symmetric arbitrageurs in the FX swap market is given by $\sum_{i=1}^{N} x^*_{\$,t}$, where we denote N as the number of arbitrageurs that have sufficiently low funding spreads in order to supply dollars in the FX swap market.

$$OF_t = x^D_{\$,t} - \sum_{i=1}^{N} x^*_{\$,t} \tag{2.8}$$

To illustrate the timing of customer-dealer trades and price-setting, Figure 2.8 depicts a two period model, in which customers and dealers trade at the beginning of each period. Immediately after each period of trading, the inter-dealer market observes order flow. Dealers then set the forward rate of the FX swap, and hence the CIP deviation Δ, to set expected order imbalances to zero for the next period of trading.

Definition [Price setting]: *The inter-dealer market sets a forward rate to set inter-dealer order flow to be zero, based on an information set that includes information on current and past prices, and customer and arbitrageur fundamentals.*

$$E_t \left[OF_t(\Delta_t) | \mathcal{I}_t \right] = 0 \tag{2.9}$$

The price-setting condition is implicitly assuming an inter-dealer market that sets a common price for all dealers. This is a reasonable assumption, as if dealers set different prices, this would not be a sustainable equilibrium as other dealers will only execute swap trades with the dealer that sets the most favorable rate.[12] Combining equations 2.8 and 2.9, we can rewrite the order flow in period t as the unanticipated components of customer demand and dealer supply of dollars in the FX swap market.

$$OF_t = x^D_{\$,t} - E\left[x^D_{\$,t} | \mathcal{I}_t \right] - \sum_{j=1}^{N} \left(x^*_{j,t} - E\left[x^*_{j,t} | \mathcal{I}_t \right] \right) \tag{2.10}$$

In the model, order flow responds to changes to demand fundamentals that are not forecast by dealers. This provides a simple decomposition of order imbalances into unexpected idiosyncratic shocks to customers and dealers, shown in equation 2.11. The first term reflects unanticipated shocks to customer type and funding spreads. For example, the inter-dealer market may not directly observe customer types, such as credit ratings and their ability to borrow dollars in alternative markets. The second term reflects unanticipated changes in funding spreads. The third term reflects rises in the cost of leverage.

[12] Moreover, inter-dealer trades are secured by daily margining practically eliminating potential differences in counterparty risk across dealers.

$$OF_t = \underbrace{\int_0^1 f(\theta_b, .) - E\left[f(\theta_b, .)|\mathcal{I}_t\right] db +}_{\text{customer type}}$$

$$\frac{1}{\rho\theta^2\sigma^2}\sum_{j=1}^{N}\left(\underbrace{c_{\$,j,t} - E\left[c_{\$,j,t}|\mathcal{I}_t\right]}_{\text{funding spreads}} + \underbrace{\phi'_{j,t}\left(\frac{x}{W}\right) - E\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right]}_{\text{leverage constraints}}\right) \quad (2.11)$$

Finally, we can solve for the equilibrium CIP deviation Δ, can be derived from setting expected order flow to zero, in equation 2.12. Intuitively, an increase in customer demand, an increase in dollar funding spreads, or a tightening of leverage constraints on arbitrageurs, leads to a widening of the CIP deviation.

$$\Delta_t = E\left[c_{\$,j,t}|\mathcal{I}_t\right] + E\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right] + \frac{\rho\theta^2\sigma^2}{N}\int_0^1 E\left[f(\theta_b, .)|\mathcal{I}_t\right] \quad (2.12)$$

We can use the framework to study the price impact of order flow, as well as the propagation of shocks to demand and supply on price-setting in the FX swap market.

Proposition 1: price impact of order flow

A positive shock to order flow in period t implies a widening of CIP deviations, with the price sensitivity $\beta = \frac{\rho\theta^2\sigma^2}{N}$.

$$\Delta_t - \Delta_{t-1} = \beta OF_t \quad (2.13)$$

The price impact of order flow is seen in equation 2.13 is governed by β, which is related positively to variance of the exchange rate, counterparty risk, and negatively related to the number of arbitrageurs N. [13]

We can further decompose price impact of order flow into unanticipated shocks to customer demand and arbitrageur supply in equation 2.14. An unanticipated change in customer demands for dollars in the FX swap market, due to a change in quality, or an unanticipated change in arbitrageur funding spreads and leverage constraints, has price impact through order flow.

[13] This contrasts to the β in microstructure models of the spot FX market, which typically measures the relative share of informed traders (Evans and Lyons, 2002). We differentiate our price impact equation in that FX swaps do not feature uninformed traders, and rely on customers that use FX swaps for largely hedging purposes.

$$\Delta_t - \Delta_{t-1} = \beta \underbrace{\int_0^1 f(\theta_b, .) - E\left[f(\theta_b, .)|\mathcal{I}_t\right] db}_{\text{customer type}} +$$

$$\frac{1}{N}\sum_{j=1}^{N}\left(\underbrace{c_{\$,j,t} - E\left[c_{\$,j,t}|\mathcal{I}_t\right]}_{\text{funding spreads}} + \underbrace{\phi'_{j,t}\left(\frac{x}{W}\right) - E\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right]}_{\text{leverage constraints}}\right) \quad (2.14)$$

In an efficient market with no limits to arbitrage, $N \to \infty$ and there is a zero price impact of order flow. In this case, there is an elastic supply of arbitrage capital to take the other side of customer trades, and dealers are able to minimise inventory and match flows. This leads us to proposition 2, which states that the price impact of order flow is more sensitive in periods of increased dispersion in funding spreads of arbitrageurs.

Proposition 2: (i) Heterogeneity in funding spreads and (ii) the tightening of leverage constraints, increases the price impact of order flow

Assume the distribution of arbitrageur funding costs is given by $c_{\$,j,t} \sim N(\bar{c_\$}, \sigma_c^2)$. An increased dispersion in funding costs ($\sigma_c \uparrow$) and an increase in the marginal cost of leverage ($\phi'_j(\frac{x}{W}) \uparrow$) leads to a decline in the number of arbitrageurs supplying dollars in the FX swap market ($N \downarrow$) and an increased price impact of order flow, $\beta \uparrow$).

Proof: The number of arbitrageurs supplying dollars in the FX swap market is proportional to the probability that the investor will conduct arbitrage, which is when the funding cost $c_{\$,j,t}$ is less than the threshold value $c^*_\$$. Utilizing the fact that the threshold value $c^*_\$ = \Delta - \phi'_j(\frac{x}{W})$, we can write the probability of conducting arbitrage in equation 2.15.

$$Prob[c_{\$,j,t} < c^*_\$] = \Phi\left(\frac{\Delta - \phi'_j(\frac{x}{W}) - \bar{c_\$}}{\sigma_c}\right) \quad (2.15)$$

The expected price impact of order flow is then given by $E[\beta] = \frac{\rho\theta^2\sigma^2}{N \times \Phi\left(\frac{\Delta - \phi'_j(\frac{x}{W}) - \bar{c_\$}}{\sigma_c}\right)}$. An increase in σ_c and an increase in the marginal cost of leverage $\phi'_j(\frac{x}{W})$ lowers the probability of conducting arbitrage, and increases the expected price impact of order flow.

Heterogeneity of funding spreads is consistent with the empirical findings of Rime et al. (2019a). When heterogeneity in funding costs increases, the remaining arbitrageurs that still face arbitrage opportunities have to supply more USD. [14] Limits to arbitrage capital are particularly pronounced

[14] Arbitrageurs face higher funding costs when they need to raise large amounts of debt to fund the arbitrage trade. For instance Money Market Funds that lend dollars are limited by regulation not to invest more than 5 per cent of their assets in a single issuer.

during quarter-end regulations, and there is micro level evidence suggesting dealers that are more leveraged are more sensitive to order imbalances and demand a higher forward premium on the contract (Du et al., 2019; Cenedese et al., 2019). Finally, we can use the framework to decompose shocks to private and public information, that gives rise to our two views of price-setting in the FX swap market in proposition 3.

Proposition 3: Public versus Private information view

Consider a shock to customer quality, arbitrageur funding spreads or leverage constraints. Denote these shocks $\epsilon_t = [\epsilon_{Q,t}, \epsilon_{C,t}, \epsilon_{L,t}]$*. Define the dealer information set* I_t*, and private information* I_t^- *is the complementary set. The price-setting equation can then be expressed in equation 2.16, where* $OF_t = \epsilon_{Q,t} + \epsilon_{C,t} + \epsilon_{L,t}|I_t^-$

$$\Delta_t - \Delta_{t-1} = \beta OF_t + \beta E[\epsilon_{Q,t} + \epsilon_{C,t} + \epsilon_{L,t}|I_t] \tag{2.16}$$

Proof: For illustration, let us partition shocks to customer quality into public and private information shocks. $\epsilon_{Q,t} = \epsilon_{Q,t}|I_t^- + \epsilon_{Q,t}|I_t$. Order flow is then defined as shocks to customer quality unanticipated by dealers: $OF = \epsilon_{Q,t} - \epsilon_{Q,t}|I_t$. Using the price-setting equation, and re-arranging terms, gives us equation 2.16.

$$\begin{aligned}
\Delta_t - \Delta_{t-1} &= \beta\epsilon_{Q,t} \\
&= \beta(\epsilon_{Q,t}|I_t^- + \epsilon_{Q,t}|I_t) \\
&= \beta(\epsilon_{Q,t} - \epsilon_{Q,t}|I_t) + \beta(\epsilon_{Q,t}|I_t) \\
&= \beta \underbrace{OF_t}_{\text{private}} + \beta\underbrace{(\epsilon_{Q,t}|I_t)}_{\text{public}}
\end{aligned}$$

Proposition 3 states that the source of information matters for price-setting. Public information shocks are impounded in the price contemporaneously. In contrast, order flow reflects private information. We provide examples of public and private information shocks in the context of the model.

Public information shocks: Examples include monetary announcements and quarter-end reporting requirements. A testable implication of our framework is that we expect to observe contemporaneous adjustment of the forward rate in response to public announcements.

Private information shocks: An example of a shock to bank quality that we test empirically is the introduction of central bank swap lines. Central bank swap lines by the Federal Reserve provide incremental dollar liquidity to sufficiently dollar constrained banks. As banks of low quality are more likely to use central bank swap lines as a way to meet dollar funding, we can interpret this as reducing customer demand for dollars via FX swaps. Crucially, if the swap line auctions to dollar constrained banks are private information, this results in a decline in order flow, causing a decline in the forward premium of the swap trade.

To conclude, the model has provided a framework to show how unanticipated shocks to customer demand, funding spreads and leverage constraints can translate to an increase in inter-dealer order flow. This causes dealers to reset the forward premium of the FX swap to offset order flow, resulting in a widening of the CIP deviation. This is consistent with microstructure theories on inventory control; dealers are sufficiently averse to holding inventory and update the forward rate as a response to avoid inventory accumulation. We test three predictions in our empirical evidence. First, based on proposition 1, we measure the price impact of order imbalances. We then test proposition 2; which states that heterogeneous dollar funding costs and leverage constraints during quarter-ends lead to increased price impact of order flow. In proposition 3, we test the public and private information views with an analysis of central bank swap lines, quarter-ends and monetary announcements.

2.5 Price Impact of Order Flow

Baseline specification

In this section, we examine the price impact of order flow. In proposition 1 of the model, we concluded that an increase in order flow in the inter-dealer market is consistent with excess demands for swapping other currencies into USD, i.e. borrowing USD through FX swaps. As dealers are averse to holding inventory, the inter-dealer market resets the forward rate to offset order flow. This leads to an increase in the forward premium and a widening of CIP deviations. Our baseline specification for testing the price impact of order flow is outlined in equation 2.17.

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_j X_{j,t} + \epsilon_t \tag{2.17}$$

The outcome variable is the daily change in 1-week CIP deviations, where negative values indicate that it is more costly to obtain USD through FX swaps relative to the direct borrowing rate in USD. Our variable of interest, β_1, measures the price impact of order flow (OF). X is a vector of control variables including the change in the U.S. Libor-OIS spreads for 1-week and 3-month maturities, the VIX index, and the USD Trade weighted exchange rate. We run the specification for all currency pairs as a panel and for the EUR/USD, CHF/USD and JPY/USD pairs separately, and divide our sample into two periods, a pre 2008 period (January 2005 to December 2007), and a post 2008 period (January 2008 to September 2017).

By dividing our sample into before and after 2008 we are able to uncover potential changes in the price impact of order flow after the global financial crisis. Our justification is that during the pre 2008 period, CIP held tightly, indicating an elastic supply of arbitrage capital. Order flow is not expected to have any significant price impact, as there are relatively short-lived periods of mispricing in the FX swap market (Akram et al., 2008). However, in the post-crisis period, arbitrage capital becomes scarce. We hypothesize that dealers adjust prices more aggressively during this period to attract the necessary arbitrage capital and balance dealer inventories.

Our results are presented in Table 2.3. In columns (1) through to (4), we test for price impact in the pre-crisis period, and in columns (5) through to (8), we test for price impact in the post-crisis period. We find that order flow has significant price impact in the post 2008 period for all 3 pairs, with a one standard deviation change in order flow widening CIP violations by up to 4 basis points based on the panel specification in column (5). In contrast, there is no significance in the pre 2008 period.

Dynamic effects

In addition to the contemporaneous price impact of order flow, we test for dynamic effects using a structural vector autoregression (VAR) framework. Following the work of Hasbrouck (1991) and Ranaldo and Somogyi (2019), we estimate the following bivariate VAR, illustrated in equations 2.18 and 2.19. In equation 2.18, a contemporaneous shock to daily order flow is impounded in the price the same day, which is consistent with the price-setting equation derived in our model framework. Conversely, we only allow for shocks to prices to affect order flow with a lag. The identification assumption is consistent with causality running from order flow to price-setting of the FX swap.

$$CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \epsilon_{1,t} \tag{2.18}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \epsilon_{2,t} \tag{2.19}$$

Based on our specification with 7 lags, we test the effects of a 1 standard deviation shock to order flow on the CIP deviations in Figure 2.9. On the left panel, we test for effects during the pre 2008 period, and observe no systematic effect of order flow on the CIP deviation for all pairs of the EUR/USD, CHF/USD and JPY/USD. In the post 2008 period, we find the CIP deviation widens by approximately 4 basis points contemporaneously, with the price impact decaying to zero approximately 3-5 days following the shock. This response is intuitive; order flow has maximum impact contemporaneously, and decays over time as dealers update their information sets. We now turn to two factors that can restrict arbitrage capital, an increase in funding cost heterogeneity and regulatory reporting during quarter-ends, that account for the increase in price impact observed in the post 2008 period.

Dispersion in funding costs and quarter-ends

Proposition 2 of the model in section 2.4 predicts that the price impact of order flow increases when heterogeneity in U.S. funding costs is large and when banks' balance sheet constraints are more binding. When funding cost dispersion increases in USD less market participants are in the position to conduct the arbitrage trade. The remaining arbitrageurs with favourable funding costs may face limits to the scalability of the arbitrage trade. Important reporting dates, such as quarter-ends, represent an opportunity to test how the price impact of order flow responds to tighter regulatory constraints. An increasing marginal cost of leverage suggests the supply of arbitrage capital becomes less elastic and the price impact of order flow increases.

To jointly test these hypotheses we run the following regression specification in equation 2.20. The variables *FundingHet* and *Qend* represent dummy variables for funding cost heterogeneity and quarter-ends, respectively. We are interested in the interaction between order flow and these variables to examine if the price impact of order flow changes when dispersion in funding costs increases and the FX swap contract crosses quarter-ends. The dummy $FundingHet$ captures days with high cross sectional dispersion among U.S. Libor panel banks in their individual submissions and when the 1-week FX swap contract matures after quarter-ends.[15] The dummy $Qend$ captures an increase in balance sheet constraints as regulatory authorities in most jurisdictions rely on quarter-end snapshot of banks' balance sheets. In addition to the control variables mentioned in the baseline specification, we also include the two dummies $FundingHet$ and $Qend$.

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_2 OF_t \times FundingHet_t + \beta_3 OF_t \times Qend_t + \beta_j X_{j,t} + \epsilon_t \tag{2.20}$$

Table 2.4 presents the results. Columns (1) to (4) measure the price impact of order flow during the pre-crisis period, and columns (5) to (8) measure price impact during the post period. Consistent with our theory, we find that the price impact of order flow is significantly higher during periods of high dispersion in Libor quotes in the post crisis period. The results suggest that larger heterogeneity in funding spreads implies that the forward rate has to adjust more aggressively to attract the necessary arbitrage capital to balance the market. Moreover, there is a substantial increase in price impact during quarter-end periods. This is also consistent with our theory of more inelastic supply of arbitrage capital when balance sheet constraints are more binding. Based on the panel regression estimates in column (5), days with high funding cost heterogeneity and quarter-end periods account for approximately three quarters of the increase in price impact after 2008.[16]

Direction of order flow

Following Rime et al. (2019a), we now test for asymmetric price impact of order flow. We expect that the price impact of order flow when it is positive, i.e. there is net pressure for swapping domestic currency into USD in the inter-dealer market. This is because high funding cost heterogeneity in USD leads to a shortage of arbitrage capital in USD. However, for negative shocks to order flow, the availability of arbitrage capital in other currencies is what matters for price impact.

We present our results in Table 2.5. Columns (1) through to (4) depict the results from regressing positive and negative order flow on changes in CIP deviations and these two variables interacted with

[15] The dispersion dummy takes value 1 when the cross sectional dispersion (difference between the maximum and the minimum submitted quote) is within the highest quartile of the distribution on the respective day and zero otherwise

[16] To arrive at this calculation, we note that the aggregate price impact of a one standard deviation order flow shock is approximately 4 basis points. After controlling for funding heterogeneity and quarter-ends, the coefficient $\beta_1 \approx 1$, implying that three quarters of the price impact is explained by these two factors.

a dummy that takes the value of 1 after 2008, and zero otherwise. As expected, neither positive nor negative order flow have any price impact prior to 2008. After 2008, both negative and positive order flow is highly significant across all currencies. This result serves as an indication that insufficient arbitrage capital in USD as an important constraint after 2008.

In addition, we run a similar regression as specified in equation 2.20 on the panel of currencies, but now with the order flow split between positive and negative order flow. Columns (5) and (6) depict the pre and post 2008 results respectively. In the post 2008 sample, shown in column (6), the price impact of positive order flow is significantly larger than for negative order flow, and during periods when funding heterogeneity is high. This is consistent with our hypothesis that high funding cost heterogeneity in USD leads to a shortage of arbitrage capital in USD, making dealers more sensitive to positive order flow (net demand for swapping domestic currencies into USD) in the FX swap market. During quarter-ends, we find both positive and negative order flow have large price impact. Dealers are aggressively adjusting the price to balance order flow independent of the direction. They are using the order flow as a signal to update the forward rate of the swap in periods when balance sheets are particularly constrained.

Bid/ask spreads and price volatility

To further substantiate the results on the price impact of order flow we examine bid/ask spreads and price volatility, calculated from high frequency quotes in the FX swap market. Bid/ask spreads are a proxy for market liquidity, and constructed as the daily intraday average of 1-week bid and ask for each currency pair. High bid/ask spreads can either indicate inventory risk for the dealer, or asymmetric information in the FX swap market. We calculate the daily standard deviation of price changes from high frequency intraday FX swap quotes as a proxy for price volatility.

We hypothesize that bid-ask spreads and intraday volatility increase during periods of funding heterogeneity and when the FX swap contract trades over quarter-ends. Tables 2.6 and 2.7 present results from regressing the bid/ask spread and price volatility on the quarter-end and funding heterogeneity variables used in specification 2.20. Columns (1) through to (3) test for effects in the pre-crisis period. Columns (4) to (9) test for effects in the post-crisis period, with additional dummies capturing the post 2015 period. First, the constant in the regression indicates that the bid/ask spreads are lowest for EUR/USD and highest for CHF/USD. This is in line with the interpretation that the EUR/USD is the most liquid currency pair while the CHF/USD is the least liquid. Similarly, price volatility increases during periods of large funding cost heterogeneity and during quarter-end periods. This is in line with order flow having stronger price impact and wider bid/ask spreads during these periods.

Most of the increase during quarter-ends have taken place after banks started to report leverage ratio to the public in 2015. In addition to lower market liquidity over quarter-ends, this may be related to leverage ratio increasing the costs of inventory for dealers. Wider bid/ask spreads act as a compensation for higher costs of being a dealer, and is consistent with empirical evidence in Krohn and Sushko (2017) which find bid/ask spreads rise during quarter-end periods.[17]

2.6 Public vs Private Information Shocks

In this section we empirically test the microstructural hypotheses of public and private information, outlined in proposition 3 of the model in section 2.4. We examine how price-setting in the FX swap market is determined in response to three different types of announcements, central bank swap lines, quarter-end reporting requirements and monetary policy surprises.

Central Bank Swap Lines

Central bank swap lines provide incremental dollar liquidity to sufficiently dollar constrained banks. Price effects have been well documented, with the rate at which the Federal Reserve lends to counterparty central banks enforcing a ceiling on CIP deviations (Bahaj et al., 2018b). We use the central bank swap lines to test the following microstructure hypotheses of how price-setting is determined in the FX swap market. If swap lines are public information, swap line auctions should be impounded in the price contemporaneously. In contrast, if the details of swap line auctions are private to dealers, price effects are due to the arrival of order flow.

We hypothesise that the swap lines constitute private information. While the date of swap line auctions are publicly known, the details of which banks have access to the swap line are unknown to dealers. Banks that have access to dollars via a central bank swap line will reduce their demand for dollar funding in the FX swap market. Therefore, dealers can update forward rates once they observe a decline in buyer initiated transactions. [18]

To test our hypothesis, we use data on Federal Reserve swap line allotments to counterparty banks during the period of 2008-2010. The data contains a record of every transaction made, with both amounts and maturity listed. The maturity of a swap line can range from one week to 1 month. At a daily frequency, we compute the total stock of allotments as the total amount of all loans made by the Federal Reserve to counterparty central banks, less any loans that have matured. The daily change in stocks provides us a flow measure of allotments. This is the most direct measure of incremental liquidity provided by the Federal Reserve to foreign (non U.S.) banks. We construct a measure of total allotments for the central bank swap line. At the height of the crisis, in October of 2008, allotments peaked at approximately \$250B to the ECB, and approximately \$100B to the BOJ. The sharp rise in allotments was due to a move by the Federal Reserve to raise the ceiling on allotment amounts. To construct a global measure of total loans to banks in the Eurozone, Japan and Switzerland, we add the total amounts outstanding for lines extended to the ECB, BOJ and SNB.

[17] They make an additional point that market structure matters for dealer pricing. In particular, the role of smaller dealers providing arbitrage capital during quarter-ends leads to an increase in the observed bid/ask spreads

[18] Alternatively, if the central bank swap lines are instead allocated to arbitrageurs supplying dollars in the swap market, we expect an increase in seller initiated transactions for dollars in the EUR/USD FX swap market. In either case, we predict an increase in allotments to reduce order flow.

We test for the impact of the constructed measure of swap line allotment flows on the CIP deviations and order flow using the multivariate VAR framework is summarized in equations 2.21, 2.22 and 2.23. We use data on 1 week FX swaps as the majority of swap allotments are of a 1 week maturity. As well as the measure of CIP deviations CIP_t and order flow OF_t, we augment the bivariate VAR in section 2.5 with a measure of swap allotment flows A_t. The identifying assumption is that shocks to swap line allotments can have contemporaneous effects on the covered interest rate parity deviation and order flow. In contrast, swap line allotments are only affected by lagged order flow and CIP deviations. We hypothesize that a positive shock to swap line allotments causes a decline in order flow, as banks substitute toward the swap line for additional dollar funding. Similarly, banks that now receive dollar funding can use their arbitrage capital by supplying dollars in the FX swap market. The decline in order flow then narrows deviations of covered interest rate parity.

$$CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{1,k} A_{t-k} + \epsilon_{1,t} \tag{2.21}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{2,k} A_{t-k} + \epsilon_{2,t} \tag{2.22}$$

$$A_t = \alpha_3 + \sum_{k=1}^{L} \gamma_{3,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{3,k} OF_{t-k} + \sum_{k=1}^{L} \delta_{3,k} A_{t-k} + \epsilon_{3,t} \tag{2.23}$$

In our baseline specification, we use $L = 7$ lags. We document the impulse response to a 1 standard deviation shock in swap line allotment flows in Figure 2.10. Consistent with our hypothesis, there is a contemporaneous decline in order flow for the EUR/USD and JPY/USD pairs. The effect on order flow is strongest for the EUR/USD. This is intuitive, given the majority of swap line allotments were extended to the ECB, which then auctioned funds to European banks that relied on dollar funding in the EUR/USD FX swap market.

Examining price effects, we see that there is a peak narrowing of CIP deviations by 5 basis points for each pair, with the peak effect occurring 2-3 days following the swap line shock. The delayed price adjustment is attributed to the timing of swap line allotments; allotments occur in periods of extreme dislocation in FX swap markets, and are responding to periods of low liquidity, high counterparty risk, and significant dollar shortages.[19] While the effect of swap lines on reducing CIP deviations has been the focus of Bahaj et al. (2018b), we contribute to this literature by showing that the price impact of central bank swap lines occurs through the channel of order flow.

Direct effects on order flow

Adding to the dynamic effects of the swap lines on order flow and CIP, we run a simple regression where we regress order flow on a dummy for the days when the results of the swap line auctions are

[19] In appendix 2.3 table 2.13 we find no effect of the swap lines on the price impact of order flow.

announced. As in our previous regressions we include the dummies for funding heterogeneity and quarter-ends. The control variables includes changes in Libor-OIS spreads (1w and 3m), VIX and broad USD index. The sample runs from January 1, 2007 to December 31, 2009, the period when the banks actively draw on the swap lines.

Table 2.8 depicts the results from the regression. In line with the VAR results, the order flow is substantially lower (less pressure to borrow USD in the FX swap market) on the days when the central banks announces the outcome of the USD auctions.

Quarter-end effects

At quarter-ends, there is an incentive for financial institutions to window-dress balance sheets in order to meet leverage requirements imposed by Basel 3. Quarter-ends can impact both customers and arbitrageurs in the FX swap market. First, quarter-ends limit capital to conduct CIP arbitrage trades, reducing the supply of dollars in the FX swap market. Second, there is evidence that a large increase in excess reserves of Euro area, Japan and Swiss banks during the post 2008 period increases the incentive to use FX swaps as an alternative source of dollar funding during quarter-ends. [20]

Quarter-end reporting obligations are known publicly to dealers, and in accordance with our microstructure hypothesis, we find evidence of contemporaneous price-setting. Figure 2.11 shows the reaction of the 1 week CIP deviation for the EUR/USD, CHF/USD and JPY/USD pairs in September 2016. Once the quarter-end period ends, the forward rate contemporaneously adjusts back to its pre quarter-end level.

To shed more light on the speed of adjustment of the forward rate over quarter-ends we exploit high frequency tick data from Thomson Reuters Tick History. In Table 2.9 we consolidate the data to the last quote each hour and identify exactly the timing when the 1 week FX forward contract trades over quarter-end. For each currency pair we look at the 1 hour change in the FX swapped USD rate (the synthetic USD rate swapped from the respective currency 1-week Libor rate) from 5 hours before to 5 hours after the contract crosses quarter-ends. Finally, the data are averaged across all quarter-ends. The data show that the contemporaneous adjustment is strong across all currency pairs, in particular after 2015 when the Leverage ratio was introduced. A large part of the adjustment happens at exactly the hour when the contract first trades over quarter-end. However, for CHF and JPY there is further adjustment in the same direction up to 2 hours following the quarter-end. Moreover, for JPY, the currency where the central bank engaged in various forms of quantitative easing (and hence provided excess reserves to banking system), there is evidence of a large contemporaneous price adjustment over quarter-ends (14 basis points) even prior to the global financial crisis.

In addition to contemporaneous adjustment of the forward rate, we also test for effects on order flow. Given market participants face heterogeneous balance sheet constraints, the contemporaneous adjustment could be too large or too small. In theory, this means that a potential effect on order

[20] This is due to FX swaps being *off balance sheet*, in contrast to short-term direct USD funding that increases leverage of the bank, see Rime et al. (2019a) for more details

flow could be in both directions.[21] We test for systematic effects on order flow by simply regressing order flow on our dummy for dates when the 1-week FX swap contract crosses quarter-ends. Table 2.10 depicts the results.

We find that order flow increases (i.e. more flow into USD) during quarter-end periods for all currency pairs in the post 2008 sample, however for JPY the effect is not statistically significant. Furthermore, we do not find that the effect on order flow changes after the Leverage ratio was introduced in 2015. These results indicate that there is a tendency that the contemporaneous adjustment around quarter-end is not large enough to curb order imbalances. Interestingly, for JPY, where the contemporaneous price adjustment is largest, the effect on order flow is smallest.

Monetary Announcements

We argue in this section that as central bank announcements are public information, dealers respond by adjusting the forward rate contemporaneously. CIP deviations are decomposed into a forward premium and the interest rate differential. In response to a change in the risk-free rate, we hypothesize that the forward premium reacts in a systematic way to offset the change in the interest rate differential. We illustrate this hypothesis in equation 2.24, where a decline in the risk-free rate r_d^f is met by an offsetting increase in the forward premium, preserving the cost of swapping euros into dollars.

$$\Delta = \underbrace{1 + r_\$^f}_{\text{direct}} - \underbrace{\frac{F \uparrow}{S}(1 + r_d^f \downarrow)}_{\text{synthetic}} \tag{2.24}$$

Figure 2.12 plots the forward premium of the EUR/USD, CHF/USD and JPY/USD in response to scheduled monetary announcements of the ECB, SNB and BOJ respectively. The ECB announcement we consider is the September 14th, 2014 announcement where the ECB lowered the deposit facility rate by 10 basis points.[22] The SNB policy announcement is on January 15th, 2015, where the interest rate target is lowered by 50 basis points to -0.75%, and the SNB lifts the floor on the CHF/EUR exchange rate.[23] Finally, the BOJ announcement we document is the 29th January, 2016 announcement when the central bank introduces a negative interest rate of 10 basis points on current account that financial institutions hold at the central bank.[24] For each announcement, we observe a widening of the forward premium of approximately a similar magnitude to the surprise change in the interest rate, with most of the adjustment occurring within an intra-day window of the announcement. The increase in the forward premium in response to a decline in the risk-free rate

[21] For example, if dealers overshoot in their expectations of the tightness of leverage constraints, then this will result in a negative order flow. Conversely, if dealers underestimate the tightening of leverage constraints, this will result in positive order flow.

[22] See ECB monetary policy decision here: `https://www.ecb.europa.eu/press/pr/date/2014/html/pr140904.en.html`

[23] see SNB press release here: `https://www.snb.ch/en/mmr/reference/pre_20150115/source/pre_20150115.en.pdf`

[24] For BOJ press release here: `https://www.boj.or.jp/en/announcements/release_2016/k160129a.pdf`

is intuitive: dealers offset the change in the risk-free rate with a change in the forward premium, keeping the CIP deviation constant.

We test our hypothesis in equation 2.24 more concretely through an event study analysis of scheduled monetary announcements. For our measure of monetary surprises, we calculate the high frequency (30 minute window) change in the 1 month overnight index swap (OIS) rate. The surprise rate is a proxy for the surprise component of the interest rate change around monetary announcements based on a measure of the risk-free rate. We run the following event study for days of scheduled announcements, by regressing order flow on the surprise measure of interest rates. Our event study results in Table 2.11 show that monetary announcements have no statistical effect on order flow.[25] The results are consistent with contemporaneous adjustment of the forward premium as dealers offset changes to the interest rate differential.

2.7 Conclusion

In this paper we detail a new channel for price discovery in FX swap markets. We identify order flow–the net of buyer and seller initiated transactions–as a fundamental signal used by dealers to update the price of the FX swap. Our key finding is that order flow has significant price impact in the post 2008 period, with no effects during the pre-2008 period. We explore two factors that restrict arbitrage capital: the increased heterogeneity of dollar funding costs and periods where the FX swap contract crosses quarter-ends, that account for the increase in price impact.

We first provide a model framework of the FX swap market. Agents supply dollars for CIP arbitrage, and demand dollars to hedge currency risk of their balance sheets. Dealers are the market-maker, and set a forward rate that equates customers net demand for dollars in the FX swap market with the supply of dollars of agents with arbitrage capital. We derive a price-setting rule in which dealers use order flow to update the forward rate of the swap.

We then test the framework empirically. Based on transaction level data for 1 week FX swaps in the inter-dealer market, we document a significant price impact of order flow in the post crisis-period, with a 1 standard deviation OF leading to a 4 basis point widening of CIP deviations. We estimate up to three quarters of the observed price impact is explained by an increase in the heterogeneity of dollar funding costs, and when the FX swap crosses quarter-end periods. Through the lens of the model, these factors lead to a reduction in arbitrage capital, and require dealers to increase the forward premium more aggressively to order flow and balance inventories.

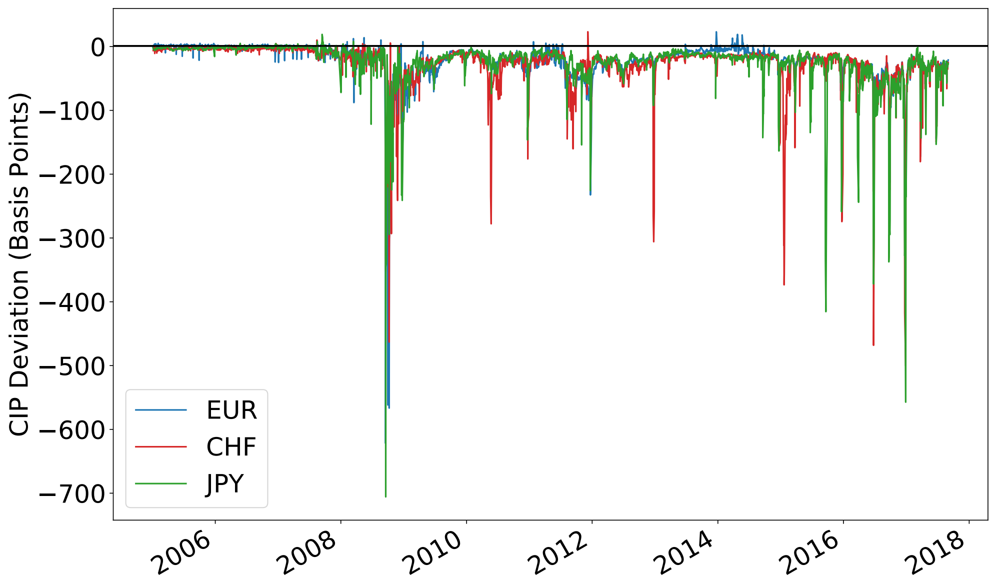
Our second empirical contribution is to distinguish between public and private information in the FX swap market. We find evidence of contemporaneous price-setting during quarter-ends and monetary announcements. During quarter-ends, we document a high-frequency jump in the forward premium that corresponds to the hour during which the FX swap contract crosses quarter-ends. This suggests that dealers are pricing the effects of quarter-ends on arbitrage capital, consistent

[25] In line with this we find no effect of monetary announcements on the price impact of order flow, see table 2.12 in appendix 2.3.

with public information. We also show gradual price adjustment through order flow in response to swap line allotments, consistent with dealers updating the forward rate in response to private information.

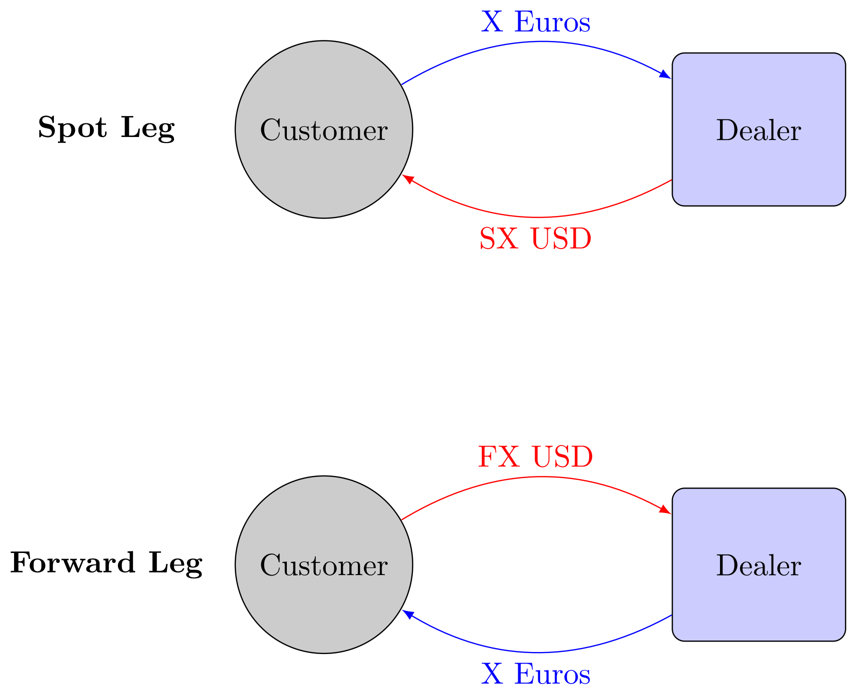
Figures

Figure 2.1
1 Week CIP Deviations for EUR/USD, JPY/USD and CHF/USD pairs



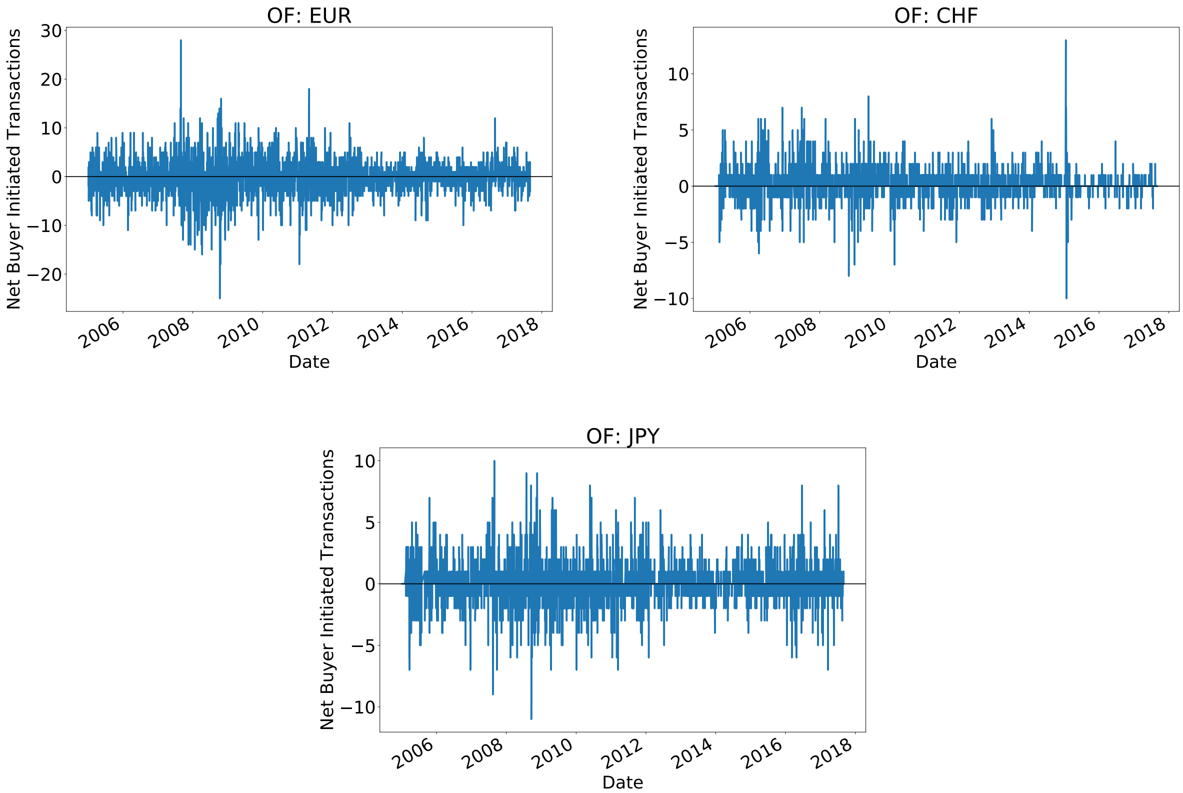
Note: This figure plots the 1 Week CIP deviation measured in basis points, obtained from Thomson Reuters Tick History. This provides a measure of CIP deviations based on a LIBOR benchmark rate. Negative deviations indicate a dollar borrowing premium for the EUR/USD, CHF/USD and JPY/USD pairs. Sample period is 01/2005-09/2017.

Figure 2.2
Foreign exchange swap



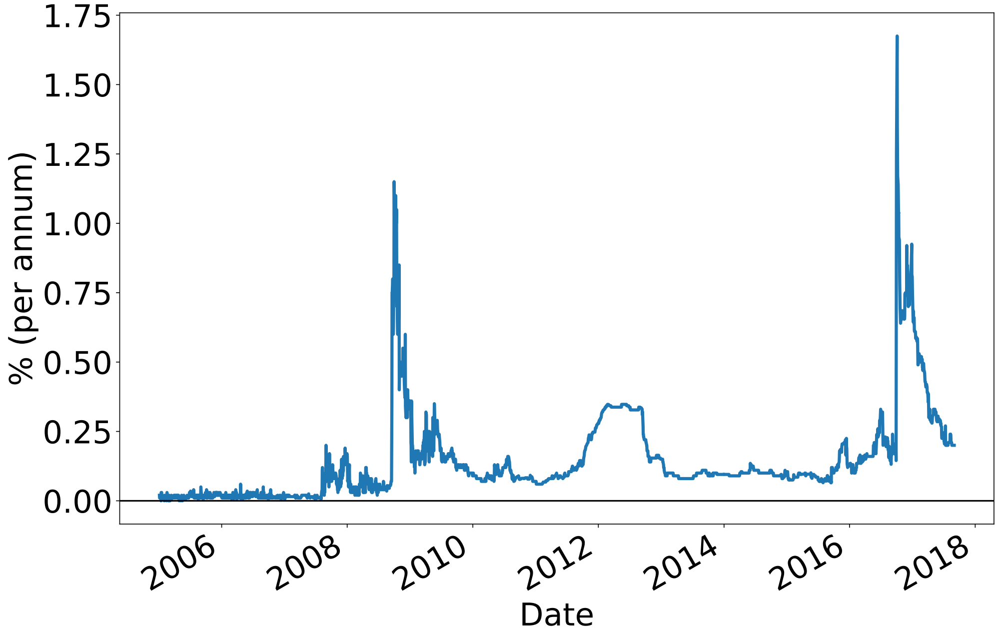
Note: FX swap is typically for maturities at less than 3m. At the spot leg, domestic currency and dollars are swapped at the prevailing spot rate. At maturity, the principals are then re-exchanged at the forward rate.

Figure 2.3
Daily Order Flow measure- EUR/USD, CHF/USD and JPY/USD



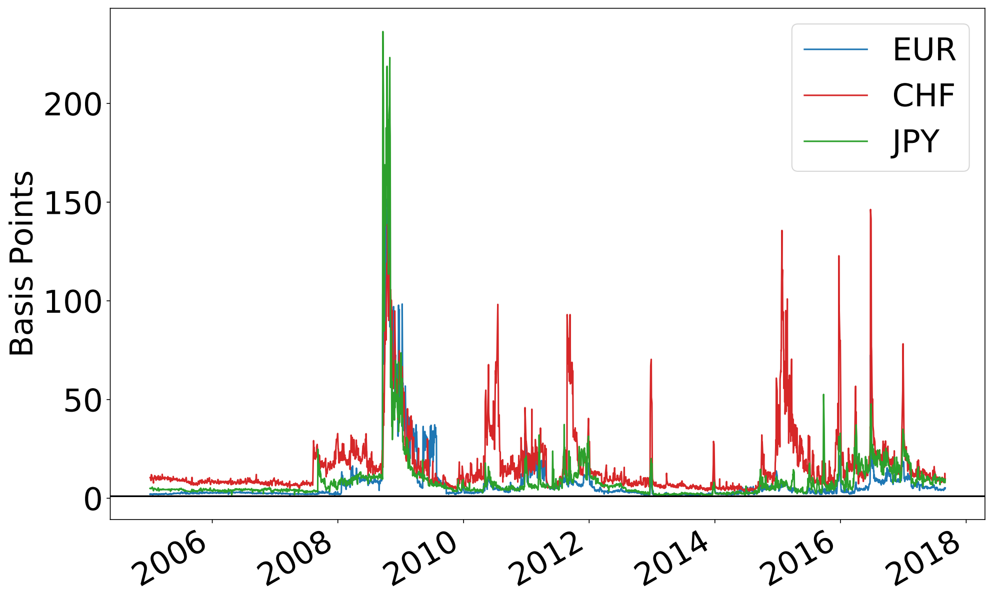
Note: Daily count order flow for EUR/USD, JPY/USD and CHF/USD pairs using the TR D2000-2, for FX swap maturities at 1 week. Order flow is given as the net of buyer initiated transactions, where buyer initiated transactions are signed $+1$ *and seller initiated transactions are signed* -1. $OF_t^{count} = \sum_{k=t_0}^{k=t} 1[T_k = B] - 1[T_k = S]$*Sample period is 01/2005-09/2017.*

Figure 2.4
Range of Libor Fixing quotes



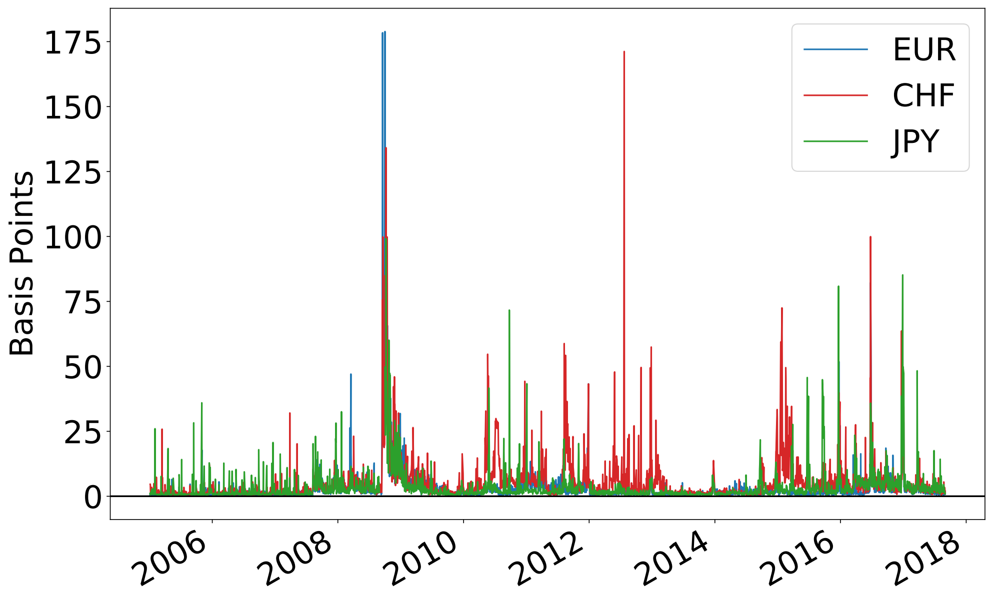
Note: The figure depicts the daily difference in percentage points between the highest and lowest submission among the contributing banks in USD Libor with 3-month maturity. The data are obtained from Bloomberg and Intercontinental Exchange (ICE). Sample period is 01/2005-09/2017.

Figure 2.5
Bid/ask spreads for EUR, CHF and JPY 1 Week FX swaps



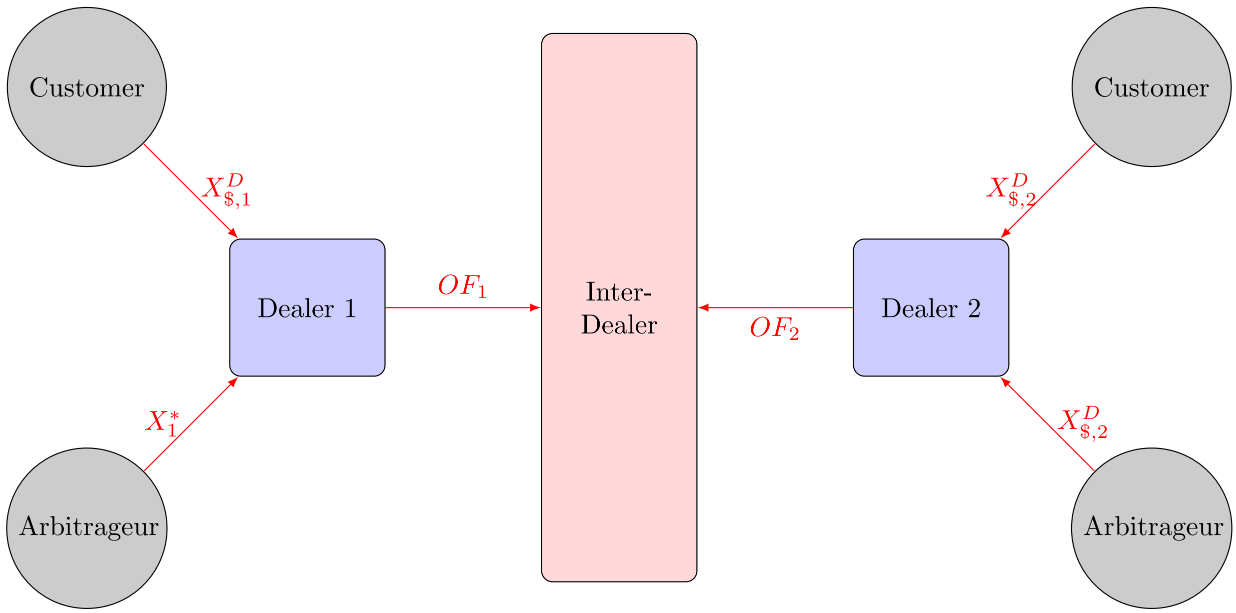
Note: The figure shows the daily average between the bid and the ask quotation based on hourly data from Thomson Reuters tick history. The bid/ask spread is expressed in basis points. Sample period is 01/2005-09/2017.

Figure 2.6
Intra-day forward rate volatility for EUR, CHF and JPY 1 Week FX swaps



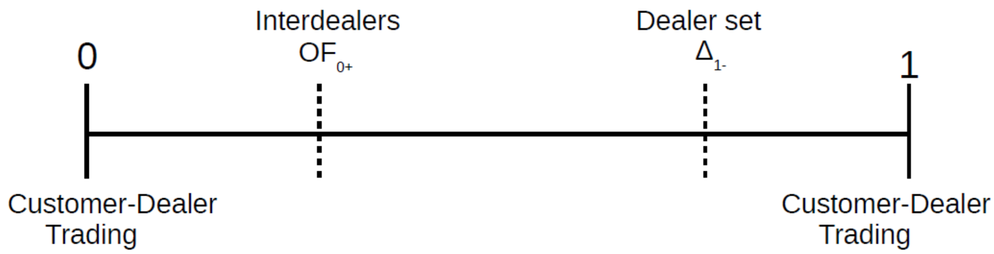
Note: The figure shows the daily standard deviation in swap points based on hourly data from Thomson Reuters tick history. The standard deviation is expressed in basis points. Sample period is 01/2005-09/2017.

Figure 2.7
Schematic of the interactions between customers, dealers and the inter-dealer market



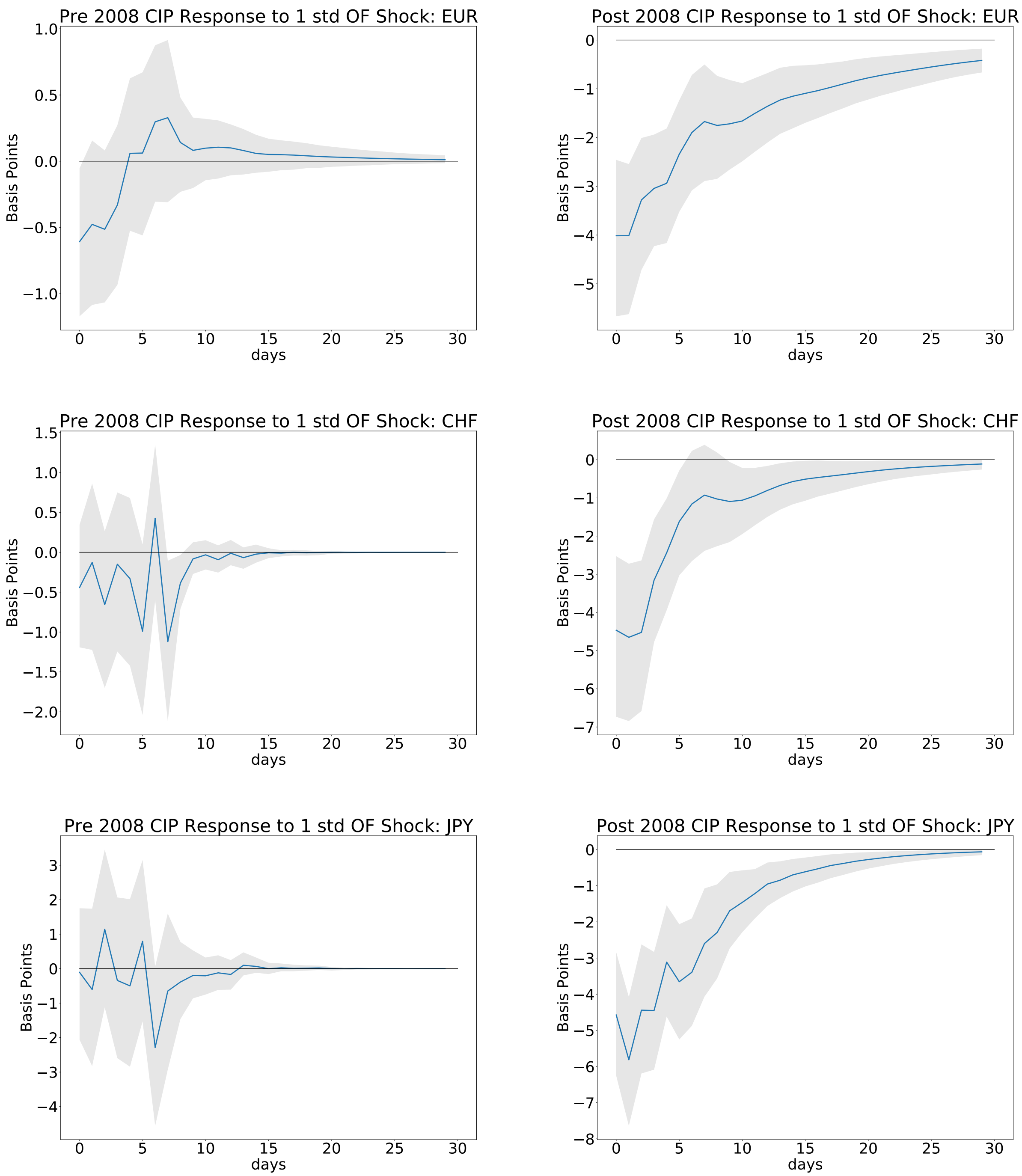
Note: This schematic illustrates the structure of the dealer-customer and inter-dealer market. Each customer has a net demand for dollar funding in the FX swap market, which we denote $x^D_\$$. The excess demands for dollar funding that cannot be met by the dealer's supply of dollars, is in turn submitted to the inter-dealer market. Aggregating net orders for swapping domestic currency into dollars gives rise to inter-dealer order flow OF which is observed as a public signal by the inter-dealer market for setting the forward rate.

Figure 2.8
Timing



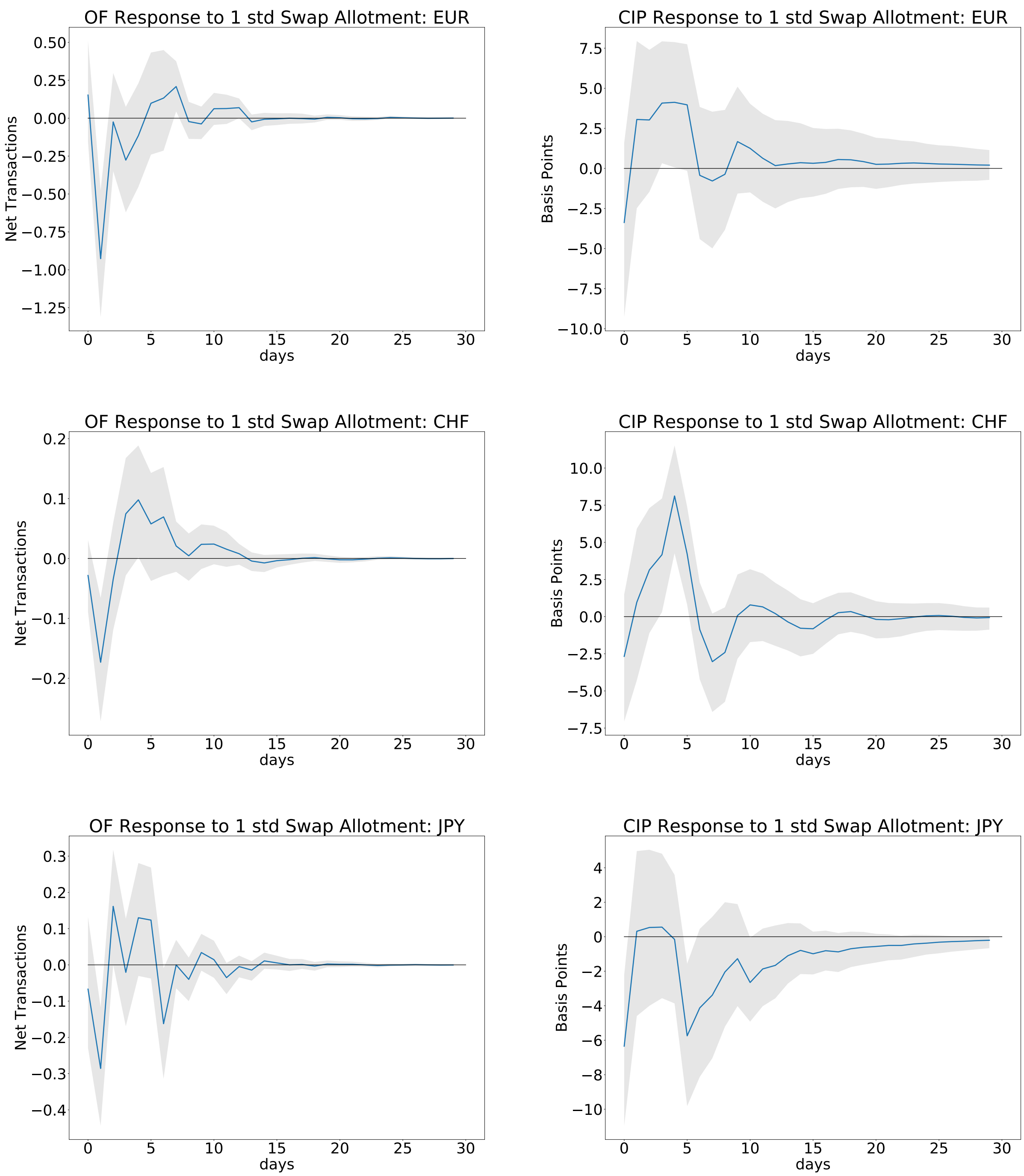
Note: This schematic illustrates the timing of the model. The customer-dealer trading is done at the beginning of each period. Following customer-dealer trading, there is an inter-dealer market which sets the forward rate following the customer-dealer trading. Dealers use inter-dealer order flow at the end of the period OF_{0+} in order to set the forward rate and CIP deviation Δ_1 in period 1.

Figure 2.9
Response of EUR/USD, JPY/USD and CHF/USD 1w CIP deviation to unit shock in count order flow in pre 2008 (left) and post 2008 (right)



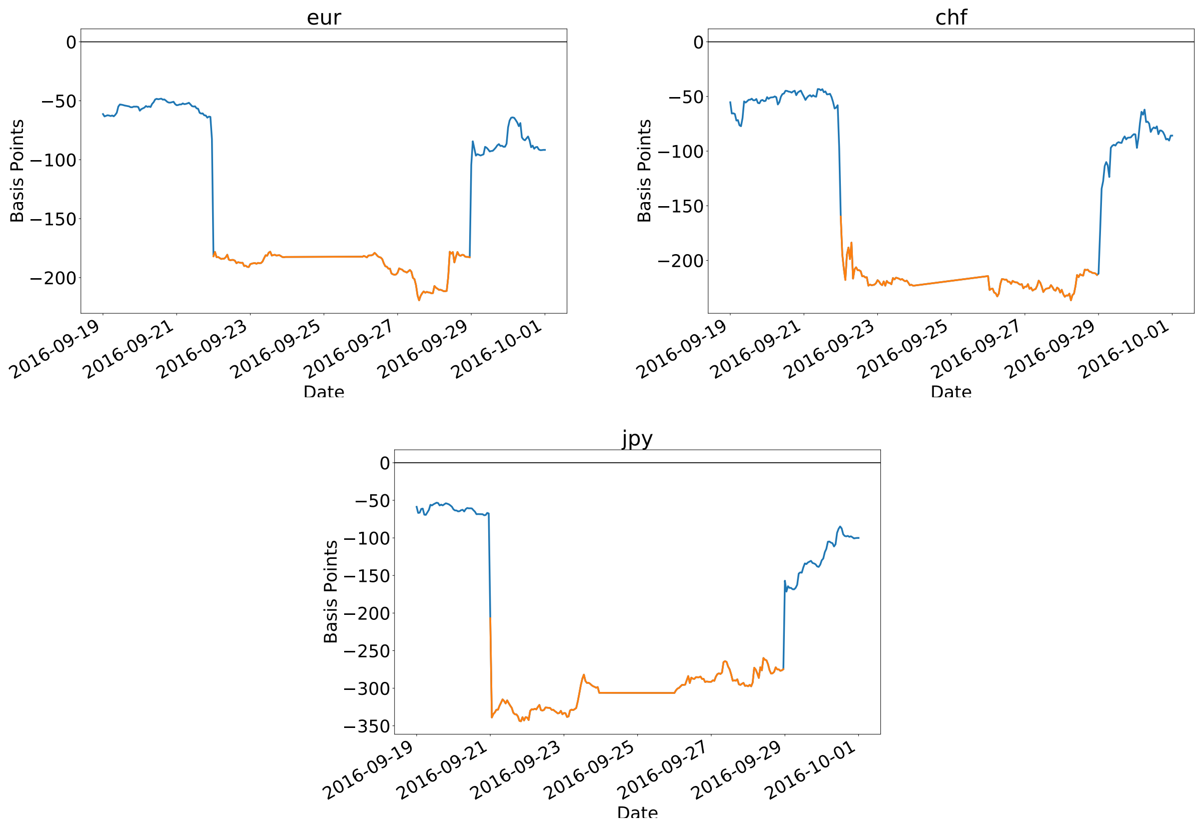
Note: This figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps, based on a bivariate VAR following Hasbrouck (1991) and Ranaldo and Somogyi (2019). Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. We condition our sample into two periods based on pre 2008 and a post 2008 period. The left panel shows response of EUR/USD, CHF/USD and JPY/USD in the pre-2008 period, and the right panel shows the response in the post-2008 period. Total sample period is from 01/2005-09/2017. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 2.10
CIP and OF Response to 1 std change in Swap Line Allotments



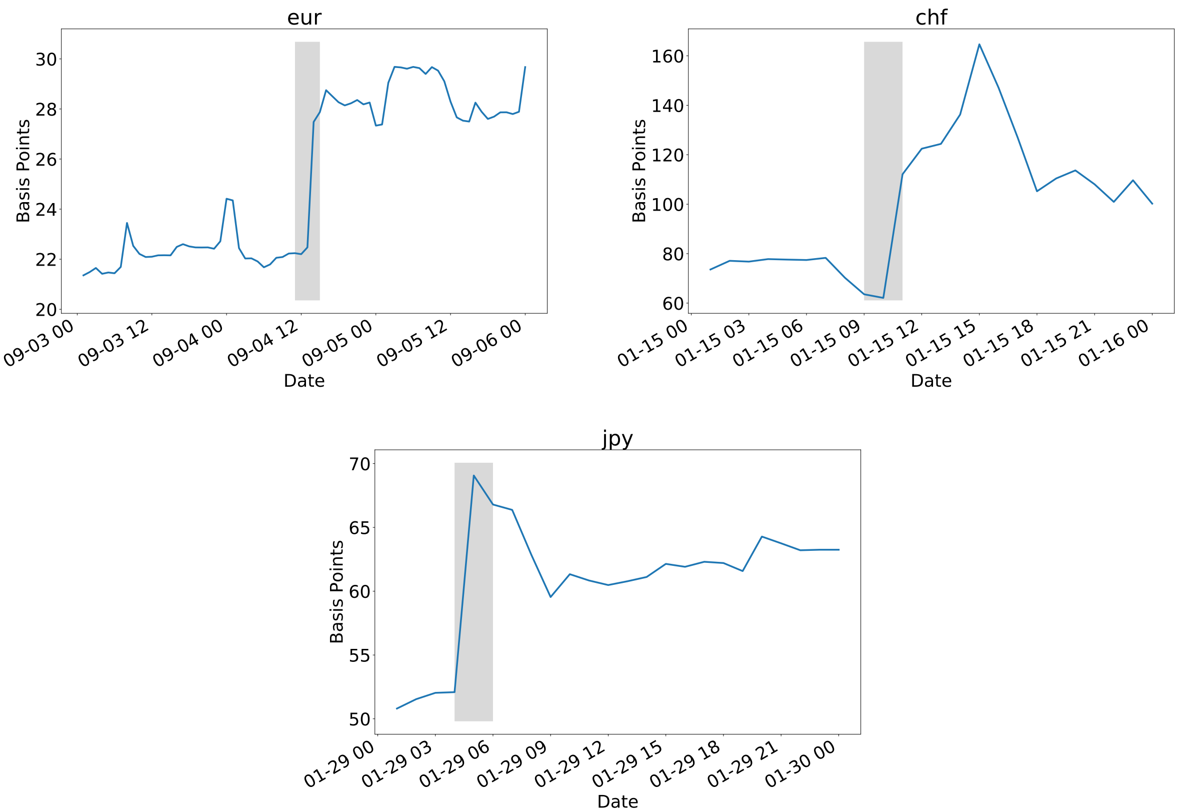
Note: This figure plots the impulse response of the change in CIP deviations and order flow to a 1 standard deviation shock in swap line allotments for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps, based on a multivariate VAR following Hasbrouck (1991) and Ranaldo and Somogyi (2019). Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. Swap line allotments measure aggregate flows of dollar loans from the Federal Reserve to counterparty central banks. The left panel shows order flow and the right panel shows the response of cip deviations of EUR/USD, CHF/USD and JPY/USD respectively. Total sample period is from 01/2007-12/2011. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 2.11
1 week EUR/USD, CHF/USD and JPY/USD CIP deviations during quarter-end in September 2016



Note: This figure examines 1 week CIP deviations for the EUR/USD, CHF/USD and JPY/USD pairs around the quarter-end period in September of 2016, with contemporaneous adjustment of the forward premium as the FX swap contract enters the quarter-end period. The CIP deviation is computed using 1 week forward, spot and domestic and dollar LIBOR rates, using intra-day data from Thomson Reuters Tick History

Figure 2.12
Response of the forward premium of EUR/USD, CHF/USD and JPY/USD pairs to scheduled monetary announcements of the ECB, SNB and BOJ



Note: This figure shows the response of 1 week forward premium in EUR/USD, CHF/USD and JPY/USD around scheduled monetary announcements of the ECB, SNB and BOJ respectively. Grey area denotes an intra-day window around the scheduled monetary announcement. In each case, the scheduled announcement changed the central bank policy rate and caused dealers to contemporaneously adjust the forward premium. The forward premium is computed using 1 week forward and spot rates, using intra-day data from Thomson Reuters Tick History

Tables

Table 2.1
Summary Statistics 1 Week CIP Deviations.

	Pre 2008				Post 2008			
	mean	sd	min	max	mean	sd	min	max
EUR/USD	-2.33	10.3	-120.0	5.1	-28.5	38.7	-621.9	73.1
CHF/USD	-8.1	17.0	-213.3	10.3	-34.0	42.7	-500.6	54.9
JPY/USD	-11.6	37.5	-347.2	33.7	-31.9	45.4	-705.8	52.7

Note: This table records summary statistics of CIP deviations in EUR/USD, CHF/USD and JPY/USD for 1 Week FX swaps. CIP deviations are expressed in basis points. Data on 1 Week Forward and Spot rates are taken from TR Tick History. Interest rates are 1 Week Libor. The full sample period is from 01/2005-09/2019, and is divided into pre and post 2008 periods.

Table 2.2
Summary Statistics count Order Flow.

	Pre 2008				Post 2008			
	mean	sd	min	max	mean	sd	min	max
EUR/USD	0.00	3.91	-16	29	-.09	3.25	-24	18
CHF/USD	0.08	1.59	-8	8	0.11	1.01	-10	7
JPY/USD	0.06	1.63	-7	8	0.00	1.41	-9	8

Note: This table records summary statistics of order flow based on trades in 1 week FX swaps using inter-dealer trades in Thomson Reuters D2000-2 Platform. Order flow is constructed as the net of buyer initiated transactions, where a transaction is signed +1 if it is swapping euros, swiss francs and yen into dollars at the spot leg of the FX swap contract. The sample period is from 01/2005-09/2017.

Table 2.3
Price impact of order flow before and after GFC

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre 2008				Post 2008			
	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}
OF	-0.16	-0.42**	-0.41	-0.01	-3.64***	-3.74***	-2.98***	-4.42***
	(0.33)	(0.18)	(0.41)	(0.96)	(0.55)	(0.89)	(0.85)	(1.05)
Constant	-0.01	-0.10	0.05	0.05	-0.02	-0.22	0.24	-0.13
	(0.35)	(0.24)	(0.50)	(0.93)	(0.27)	(0.45)	(0.48)	(0.47)
Observations	2,084	713	712	659	6,703	2,238	2,234	2,231
R-squared	0.00	0.01	0.00	0.01	0.08	0.11	0.04	0.09
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, and the USD Trade weighted exchange rate. The full sample from Jan 1, 2005 to Sep 1, 2017 is split into pre and post 2008. Data is daily. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.4
Price impact of order flow; funding constraints and quarter-ends

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre 2008				Post 2008			
	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}
OF	-0.46	-0.47**	-0.50	-0.57	-1.04**	-1.20**	-2.02*	0.06
	(0.31)	(0.20)	(0.45)	(0.94)	(0.48)	(0.47)	(1.03)	(0.60)
OF × FundingHet	6.00	0.91	0.32	37.08	-4.14***	-4.84**	-0.34	-6.36***
	(6.46)	(4.30)	(2.30)	(26.70)	(1.18)	(2.17)	(1.57)	(1.68)
$Qend \times OF$	1.54	-0.13	0.29	3.16	-9.27***	-2.83	-9.09*	-15.97***
	(1.40)	(0.57)	(0.82)	(3.88)	(3.26)	(2.95)	(5.32)	(6.06)
Constant	0.13	0.03	-0.04	0.48	0.39*	0.24	0.92**	0.19
	(0.36)	(0.25)	(0.52)	(0.96)	(0.21)	(0.28)	(0.41)	(0.37)
Observations	2,084	713	712	659	6,703	2,238	2,234	2,231
R-squared	0.01	0.01	0.01	0.04	0.11	0.13	0.07	0.16
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. FundingHet is a dummy variable that takes the value 1 when the daily dispersion in individual panel bank's 3-month Libor quotes is among the 25 per cent largest values, and zero otherwise. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Additionally, the following variables are included in the regression specification but not shown in the Table; Qend and FundingHet. Data is daily. The sample runs from Jan 1, 2005 to Sep 1, 2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.5
Price impact of order flow; direction of flow

	(1) ΔCIP_{panel}	(2) ΔCIP_{eur}	(3) ΔCIP_{chf}	(4) ΔCIP_{jpy}	(5) ΔCIP_{panel}	(6) ΔCIP_{panel}
OF × 1$[OF > 0]$	-0.12	-1.22*	-0.28	0.97	-0.88	-1.42*
	(0.67)	(0.67)	(0.35)	(2.13)	(0.60)	(0.72)
OF × 1$[OF < 0]$	0.38	0.02	-0.25	1.26	0.01	-0.86
	(0.47)	(0.51)	(0.95)	(0.97)	(0.47)	(0.86)
OF × 1$[OF > 0]$ × post2008	-4.39***	-5.07**	-2.58*	-6.04*		
	(1.23)	(2.31)	(1.38)	(2.77)		
OF × 1$[OF < 0]$ × post2008	-3.30***	-1.32	-2.99**	-5.32		
	(1.01)	(1.03)	(1.51)	(2.58)		
OF × 1$[OF > 0]$ × FundingHet					11.25*	-5.31**
					(6.23)	(2.20)
OF × 1$[OF < 0]$ × FundingHet					5.89	-2.83*
					(7.46)	(1.65)
OF × 1$[OF > 0]$ × Qend					3.43	-6.98*
					(2.42)	(4.24)
OF × 1$[OF < 0]$ × Qend					-0.96	-12.33*
					(1.28)	(7.48)
Constant	0.10	0.36	-0.02	-0.02	0.41	0.50
	(0.51)	(0.50)	(0.52)	(1.35)	(0.52)	(0.34)
Observations	8,787	2,951	2,946	2,890	2,084	6,703
R-squared	0.05	0.10	0.03	0.04	0.01	0.11
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Post2008					No	Yes

Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. 1$[OF > 0]$ *takes the order flow value if the order flow is positive, zero otherwise. Positive order flow implies a pressure to obtain USD spot and sell USD forward (i.e. borrow USD).* 1$[OF < 0]$ *takes the order flow value if the order flow is negative, zero otherwise. FundingHet is a dummy variable that takes the value 1 when the daily dispersion in individual panel bank's 3-month Libor quotes is among the 25 per cent largest values, and zero otherwise. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Post 2008 is a dummy that takes the value 1 after Jan 1 2008, and zero otherwise. The Table only shows the relevant coefficients. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Additionally, the dummies for FundingHet, Qend and Post2008 are included, but not shown. Data is daily. The sample runs from Jan 1, 2005 to Sep 1, 2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.6
Bid/ask spreads

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Pre 2008			Post 2008					
	EUR	CHF	JPY	EUR	CHF	JPY	EUR	CHF	JPY
FundingHet	0.02	14.05***	2.21**	10.95***	5.07***	13.39***	17.40***	10.13***	18.67***
	(0.19)	(2.08)	(1.09)	(0.95)	(0.89)	(1.13)	(1.59)	(1.32)	(1.95)
Qend	0.01	-0.41	0.27	3.64***	3.59**	4.81**	2.69	0.61	3.25
	(0.05)	(0.53)	(0.34)	(1.33)	(1.70)	(1.91)	(1.63)	(1.48)	(2.44)
post2015							-2.16***	10.74***	2.32***
							(0.28)	(1.40)	(0.40)
post2015 × Qend							2.57	10.68**	5.36*
							(2.36)	(4.97)	(2.98)
post2015 × FundingHet							-13.53***	-17.89***	-13.50***
							(1.63)	(2.01)	(2.01)
Constant	2.51***	9.56***	4.52***	5.61***	16.54***	6.11***	6.06***	14.53***	5.71***
	(0.01)	(0.15)	(0.07)	(0.18)	(0.42)	(0.19)	(0.22)	(0.39)	(0.23)
Observations	756	745	691	2,434	2,437	2,438	2,434	2,437	2,438
R-squared	0.00	0.12	0.02	0.10	0.02	0.10	0.17	0.07	0.13

*Note: This table regresses bid/ask spreads for 1 week FX swap quotes based on high frequency data from Thomson Reuters Tick History database on dummies for Funding Heterogeneity (FundingHet) and dates when the 1 week contract crosses quarter-ends (Qends) for three currency pairs (EUR/USD, CHF/USD and JPY/USD). Column (1) to (3) depict the results from a sample that runs from January 1,2005 to December 31, 2007, while column (4) to (6) are based on a sample period that runs from January 1, 2008 to September 1, 2017. In column (7) to (9) the interaction terms between a dummy that takes the value 1 from January 1, 2005 and onwards (zero otherwise) and funding heterogeneity and quarter-ends are added. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.7
Price volatility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Pre 2008			Post 2008					
	EUR	CHF	JPY	EUR	CHF	JPY	EUR	CHF	JPY
FundingHet	0.04***	0.03***	0.07**	0.04***	0.02***	0.03***	0.06***	0.04***	0.03***
	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.00)
Qend	0.00	0.01	0.01*	0.04***	0.03***	0.05***	0.02**	0.01	0.02**
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
post2015							-0.01***	0.02***	0.01***
						(0.00)	(0.01)	(0.00)	
post2015 × Qend							0.08***	0.07***	0.14***
						(0.03)	(0.03)	(0.03)	
post2015 × FundingHet							-0.04***	-0.07***	-0.02***
						(0.01)	(0.01)	(0.01)	
Constant	0.01***	0.02***	0.02***	0.02***	0.05***	0.02***	0.02***	0.05***	0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	756	745	691	2,434	2,437	2,396	2,434	2,437	2,396
R-squared	0.05	0.03	0.05	0.05	0.02	0.08	0.08	0.05	0.15

*Note: This table regresses daily price volatility for 1 week FX swap quotes based on high frequency data from Thomson Reuters Tick History database on dummies for Funding Heterogeneity (FundingHet) and dates when the 1 week contract crosses quarter-ends (Qends) for three currency pairs (EUR/USD, CHF/USD and JPY/USD). Column (1) to (3) depict the results from a sample that runs from January 1,2005 to December 31, 2007, while column (4) to (6) are based on a sample period that runs from January 1, 2008 to September 1, 2017. In column (7) to (9) the interaction terms between a dummy that takes the value 1 from January 1, 2005 and onwards (zero otherwise) and funding heterogeneity and quarter-ends are added. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.8
Effect on order flow; Swap Lines

	(1)	(2)	(3)	(4)
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}
SwapLines	-0.21**	-0.28*	-0.04	-0.50*
	(0.11)	(0.15)	(0.19)	(0.26)
Constant	0.03	-0.14*	0.18***	0.07
	(0.04)	(0.08)	(0.06)	(0.07)
Observations	1,444	480	482	482
R-squared	0.02	0.06	0.01	0.04
Controls	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of quarter-end on for 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. SwapLine is a dummy variable that takes the value 1 on days when there was initial take up in any of the swap lines between the Fed and foreign central banks, zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Dec 31, 2009. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.9
Price adjustment quarter-end for EUR/USD, CHF/USD and JPY/USD

	EUR/USD				CHF/USD				JPY/USD			
Hour	2005-2007	2008-2013	2013-2015	2015-2017	2005-2007	2008-2013	2013-2015	2015-2017	2005-2007	2008-2013	2013-2015	2015-2017
-5	0	-0.5	0	0.3	-0.1	2.1	-0.2	-1.8	-0.2	0.1	-0.3	-0.3
-4	0.3	1	0	0.2	-0.2	1.8	-0.3	-0.1	0.2	1	-2.1	-0.3
-3	-0.1	-0.8	0.2	0.2	-0.1	-1	0.1	-3.3	-0.8	-0.9	-0.3	-0.5
-2	0.1	-0.2	2.1	1.7	0.2	-4.7	1.3	2.4	-0.8	2.2	-0.4	15.6
-1	0	0.9	0	9	1.3	2.7	-1.4	1.6	0.7	0.1	0.4	2.7
0	0.8	0.8	-1.6	22.7	0.2	2.3	-2.8	22.3	14.3	5.1	16.3	55.2
1	0.5	0	-0.4	6	-3.2	-3.2	2	16.2	-4.3	4.5	10.8	36
2	0.9	2.2	-0.3	0.8	0	1.1	-1.1	5.2	-1.2	4	-2.8	32.9
3	0.2	2.9	-0.2	0	-0.1	3.7	0.2	12.2	1.1	1.3	0.4	0
4	-0.1	0	-0.4	-0.7	0.4	-2	0.5	-2.2	-0.3	1	1.1	0.9
5	0.2	-0.4	0	0.1	-0.1	1.3	-0.7	-6.5	-0.2	0.2	0.7	10.3

Note: This table illustrates the hourly change in the FX swapped (synthetic) USD rate calculated from Libor from 5 hours before to 5 hours after the 1 week FX swap contract matures after quarter-end. 0 denotes the hour when the contract first matures after quarter-end. The numbers are in basis points and represent the average of all quarter-ends within the sample period.

Table 2.10
Effect on order flow; Quarter-end

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Pre 2008				Post 2008					
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}	OF_{panel}	OF_{panel}
Qend	0.14	-0.03	0.61***	-0.17	0.13***	0.15*	0.16**	0.08	0.22***	0.14**
	(0.10)	(0.14)	(0.18)	(0.19)	(0.05)	(0.09)	(0.07)	(0.08)	(0.08)	(0.06)
post2013									0.03	
									(0.03)	
post2013 × Qend									-0.29***	
									(0.10)	
post2015										-0.01
										(0.02)
post2015 × Qend										-0.02
										(0.09)
Constant	0.05**	-0.04	0.11***	0.07*	0.03**	-0.04*	0.11***	0.02	0.02	0.03**
	(0.02)	(0.04)	(0.04)	(0.04)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Observations	2,095	724	712	659	6,723	2,240	2,241	2,242	6,723	6,723
R-squared	0.01	0.01	0.03	0.04	0.01	0.01	0.00	0.01	0.01	0.01
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of quarter-end on 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end, zero otherwise. Post2013 and post2015 are dummy variables that are 1 from Jan 2013 and Jan 2015, respectively, zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.11
Effect on order flow; Monetary Policy surprises

	(1)	(2)	(3)	(4)
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}
Δois	-1.86	-2.28	-1.18	13.86
	(1.59)	(3.84)	(1.85)	(10.07)
Constant	-0.05	0.02	-0.03	-0.09
	(0.05)	(0.07)	(0.11)	(0.09)
Observations	363	136	87	122
R-squared	0.01	0.04	0.02	0.09
Controls	Yes	Yes	Yes	Yes
Post2008	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of monetary policy surpirses on 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. ΔOIS is the 30 min change in the 1-month OIS rate (Overnight Index Swaps - a proxy for the risk free rate) in the respective currency around the central bank policy announcement. Monetary announcements in EUR, CHF, JPY and USD are considered. In the case of US announcements the sign of the change in the OIS is switched so that a positive change in the OIS always proxy an increase in the interest rate differential towards the US (i.e foreign currency rate minus the US rate). Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

A: Additional Tables

Table 2.12
Price impact of order flow; Monetary announcements

	(1) ΔCIP_{panel}	(2) ΔCIP_{eur}	(3) ΔCIP_{chf}	(4) ΔCIP_{jpy}	(5) ΔCIP_{panel}	(6) ΔCIP_{eur}	(7) ΔCIP_{chf}	(8) ΔCIP_{jpy}
OF	-0.34	-0.23	-0.41	0.03	-0.88	-1.26**	-2.09*	0.57
	(0.49)	(0.39)	(0.72)	(1.53)	(0.54)	(0.52)	(1.12)	(0.74)
MP	2.20	6.19*	-14.32	2.02	-1.08	1.71	-5.41	-0.74
	(3.72)	(3.52)	(12.09)	(7.07)	(1.53)	(1.43)	(3.79)	(2.39)
MP*OF	-3.14	-0.59	-24.40*	-3.54	-3.18	3.34	3.11*	-7.45
	(1.94)	(2.12)	(13.41)	(3.46)	(3.87)	(2.55)	(1.65)	(5.79)
Constant	0.16	-0.20	0.16	0.48	0.44*	0.22	1.04**	0.25
	(0.60)	(0.40)	(0.85)	(1.68)	(0.25)	(0.34)	(0.49)	(0.45)
Observations	2,053	713	706	634	6,675	2,211	2,233	2,231
R-squared	0.01	0.03	0.01	0.04	0.11	0.13	0.07	0.16
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Post2008	No	No	No	No	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. MP is a dummy variable that takes the value 1 on days when the central bank disseminates its monetary policy decision, and zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate, FundingHet, OF*FundingHet, Qend, Qend*OF. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 2.13
Price impact of order flow; Swap lines

	(1) ΔCIP_{panel}	(2) ΔCIP_{eur}	(3) ΔCIP_{chf}	(4) ΔCIP_{jpy}
OF	-0.84	-3.06*	-0.75	0.66
	(0.68)	(1.75)	(0.62)	(1.05)
SwapLine	-0.42	0.06	-2.07	1.62
	(2.99)	(3.88)	(5.26)	(5.95)
OF*SwapLine	2.75	5.25	-3.12	4.86
	(3.06)	(6.81)	(3.05)	(4.47)
Constant	-0.39	-0.34	-0.25	-0.92
	(0.56)	(1.22)	(0.78)	(0.94)
Observations	1,444	480	482	482
R-squared	0.17	0.16	0.07	0.38
Controls	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. SwapLine is a dummy variable that takes the value 1 on days when there was initial take up in any of the swap lines between the Fed and foreign central banks, zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2007 to Dec 31, 2009. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Chapter 3

International financial frictions, bank lending and firm level activity

3.1 Introduction

An important aspect of global financial intermediaries is that a significant part of their transactions is financed by USD-denominated unsecured credit. The dollar liabilities of non-U.S. banking institutions have grown rapidly since the early 2000s, and are estimated currently at above $10 trillion based on data from the Bank for International Settlements (Ivashina et al. (2015)). This is comparable to the size of the combined balance sheet of all U.S. banks.[1] A large part of this borrowing activity is then transferred to loans to customers in local currency.

Sizable USD denominated liabilities can expose banks to an additional source of funding risk to the extent that the cost of USD denominated short-term funding does not change one to one with the change in domestically denominated short-term funding. Our point of departure is the empirical observation that - post-crisis - there has been substantial variation in the cost advantage of borrowing short-term USD relative to domestic short-term funding, also when accounting for FX hedging cost ("USD cost advantage"). This form of covered interest parity deviation exposes banks to a new source of variation in funding costs, and can potentially transmit to the domestic economy via a bank lending channel.[2] Although deviations from covered interest parity has gotten substantial attention in the academic literature (Rime et al., 2019a; Du et al., 2019), the real implications is not yet fully understood. In this paper, we aim to fill this gap.

Analyzing the impact of FX cost advantages is empirically challenging, because the debt structure of banks is endogenous to the composition of their assets, to investors' preferences, and to the cost of financing. In this paper, we overcome these challenges by exploiting an arguably exogenous change in the USD cost advantage for internationally active Norwegian banks, which took place during the European sovereign debt crisis of 2011. At that time, U.S. money market funds expanded USD-denominated credit to highly rated Norwegian banks (as well as to other highly rated banks from neighboring Scandinavian countries, Australia, among others), while at the same decreasing supply to Euro area banks (see Figures 3.1 and 3.2). This resulted in funding becoming less expensive for banks that had access to the USD-denominated debt market, versus the rest of the domestic banking system.

We present two sets of results. First, internationally active banks responded to the USD cost advantage by raising more USD funding. The increase in USD foreign funding were not offset by similar decreases in other funding sources, leading to an overall expansion of bank balance sheets. A sizable fraction of the funds raised in USD-denominated short-term funding markets were lent domestically to Norwegian firms.[3] As a result of the shock to the USD cost advantage, bank short-term funding to total assets increased by approximately 3 percentage-points. Second, the expansion in domestic credit translated into higher investment at the firm-level – especially in total fixed assets

[1] See Ivashina et al. (2015) for more details on the role of dollar-denominated financial intermediation.

[2] Strictly speaking, and in line with the terminology in Rime et al. (2019a), we are measuring the Law of One Price as we are comparing borrowing costs across currencies

[3] Approximately half of the initial increase in foreign funding was lent to domestic firms. The bulk of the remaining funds were deposits at foreign central banks.

and PP&E (capital). In aggregate, the effects were large: according to our estimates, aggregate capital grew by 2-2.9% more due to this shock, suggesting that covered interest parity deviations have sizable economic implications.

In order to analyze the impact of USD cost advantages, we use data from four different sources. First, we use data from Bloomberg to compute the USD cost advantages. Second, we use a supervisory bank-level database to identify banks operating in short-term foreign funding markets, in addition to obtaining data on several bank outcomes. Third, we use an annual administrative loan-level database on all firm-bank connections to investigate the loan-level impact of USD cost advantages. Fourth and finally, we complement our data with annual firm-level data to trace out the impact of banks' adjustment to the shock to the real economy.

Our main identification strategy exploits the fact that to take advantage of USD cost advantages, banks either already had to have in place the necessary infrastructure to issue commercial paper, or had to have a branch in the U.S. Both entails substantial fixed costs, and hence only a subset of the banks ("internationally active banks") in our sample could effectively access lower funding costs via CIP deviations.[4] Motivated by this, we aim to identify the real implications of USD cost advantages by comparing outcomes at the bank- and loan-level for internationally active banks with other domestic banks. The assess the real implications, we compare outcomes for firms borrowing from internationally active vs. domestic banks. In our main analysis, we restrict attention to the period 2009 - 2012, and focus on the one-time increase in the USD cost advantage associated with the Eurozone crisis. In the robustness, however, we show that our findings at the bank-level are not confined to this particular episode but holds more generally.

We first explore the underlying mechanism of the failure of the CIP in the market for short-term bonds issued by highly rated Scandinavian banks. CIP represents a key pillar in international finance, and it postulates that the cost of borrowing in a foreign currency plus the cost of hedging hedging FX risk should be equal to the cost of borrowing domestically. CIP is a no-arbitrage condition, which requires a risk free *two-way trade* between the interest rate in the funding leg and the unsecured funding rate with the same maturity as the FX-swap contract ((Rime et al., 2019a)). Prior to the financial crisis, CIP was known to hold across a wide range of financial instruments. This changed after the crisis. The breakdown of CIP has been dubbed as "one of the most significant developments in global financial markets"(Du et al., 2019).[5] We argue that an important potential explanation for the deviation in CIP for highly Scandinavian banks was the shift in the supply of funds from US money market funds.

Second, we compare the evolution of bank-level outcomes for banks that are active in short-term USD funding markets ("internationally active banks") with other Norwegian banks. Our main identifying assumption at the bank-level is that the difference in outcomes between the two groups

[4] Norwegian banks operating in FX short-term markets are typically larger banks.

[5] Several papers have investigated deviations of CIP. Different explanations include regulation (Du et al., 2019), market segmentation (Rime et al., 2019a), arbitrage limits (Ivashina et al., 2015), changes in bank balance sheet (Avdjiev et al., 2019), and swap market imperfections (Liao, 2020).

of banks would have been the same in the absence of the funding shock. More specifically, we show that during this episode, internationally active banks increased the growth in foreign borrowing, leading to approximately a relative increase in the share of foreign funding to total assets of 3 %-points. Contemporaneously, corporate lending relative to total assets increased by approximately 2 %-points.

We then trace out how the impact of the shock to bank financing translates at the loan amounts and firm activity. We show that credit growth is approximately 6% higher on average for firms borrowing from internationally active banks. We also show that the change in the interest rate on loans to the same firm within the same year is roughly 146 bps lower when borrowing from internationally active banks. Overall, our results suggest that the favorable foreign funding shock to bank financing translated into an expansion of domestic credit.

Using firm-level data we trace out the impact of the expansion of credit on economic performance. Importantly, the greater availability of funding on better terms from treated banks may have led to less borrowing from other sources, thus weakening the real implications of the shocks. However, we show that this type of substitution hardly took place. The increase in borrowing by firms is comparable to the total growth in debt. This finding suggests that firms may have been financially constrained during normal times. Rather surprisingly, we do not find that cheaper short-term funding at banks was channeled to finance short-term firm assets, such as trade-credit. On the contrary, firms that borrowed from treated banks increased their fixed tangible assets, and in particular capital and fixed financial assets. But, we find no effect on intangible capital or on current assets. More precisely, firms borrowing from internationally active banks had about 1.3% growth in fixed assets compared to other firms, and 2.3% higher growth in sales. The increase in borrowing from banks is driven by both an increase in short-term and long-term debt. As we discuss in the policy section, such outcome increases the potential liquidation risks not only at the bank level (due to rollover risk and fire sales), but also at the firm level, as failure to refinance can bring about high liquidation costs for firm assets.

As a final step, we use our estimates to provide a back-of-the-envelope estimate of the importance of the shock in the aggregate. Assuming there are no general equilibrium effects, and that the sales and capital growth of firms borrowing from banks that are not internationally active constitutes a reasonable counterfactual, we find that sales were 1.2-5% higher in 2011-2012 due to the foreign funding shock. The corresponding effect on capital was 2-2.9%.

Throughout our analysis, we employ numerous robustness exercises to ensure the validity of our empirical approach. At the bank-level, we employ a dynamic difference in differences to explicitly test for parallel trends in outcomes for the two groups prior to and after the shock. At the loan-level, first we follow Khwaja and Mian (2008) for the sample of firms borrowing from both an internationally active and non-internationally active bank, and only look at within firm-year variation. For the full sample of firms, we control for firm demand by employing a granular set of fixed effects. Second, we focus on both quantities and prices, which allows us to plausibly argue that we isolate changes in credit due to supply factors rather than demand. Finally, at the firm-level we saturate our specifications with industry-year fixed effect to control for confounding firm shocks.

Our paper has implications for the macroeconomy, bank regulation and monetary policy. Given the close links between financial markets and real economic outcomes, deviations from CIP have real economic implications beyond credit markets. As financial institutions finance themselves issuing debt in numerous currencies, deviations from CIP between two currencies affect the funding mix and the average cost of capital for internationally active banks. Changes in the extent to which CIP holds then affect credit supply, which in turn affects the macroeconomy. Until now little has been shown about the quantitative strength of this channel, about how it ultimately affects real economic outcomes, and what policymakers should do about it.

The CIP shock is a short-term funding shock, and as such it is distinct from monetary policy shocks that are typically persistent in time, often because they affect the entire yield curve. Our focus is on a change in short-term funding costs that may rapidly reverse. This allows us to examine how transitory liquidity shocks affect the supply of credit. In this respect, the short-term nature of the shock sets us apart from the academic and policy discussion which focuses mainly on long-term refinancing. Moreover, as the shock originated outside Scandinavia, it was arguably orthogonal to Norwegian monetary policy. This gives us a unique opportunity to study fluctuations in the local credit supply that are unrelated to domestic monetary policy.

Related literature This article adds to the literature on how financial frictions affect bank lending behavior. A number of these papers study the impact of shocks during crises times, generally finding adverse effects on lending that cannot be substituted by alternative sources. Cornett et al. (2011) show that banks that relied more heavily on stable sources of financing, such as core deposit and equity capital financing, continued to lend more relative to other banks. Iyer et al. (2014) study the dry-up of interbank markets during the financial crisis, which hurt banks that were dependent on such markets. Avdjiev et al. (2019) study the relationship between dollar strength, CIP deviations and bank-level flows. We focus on loan- and firm-level flows, as well as firm level activity.

Closer to our work, Ivashina et al. (2015) and Brauning and Ivashina (2017) focus on the dollar's central role in international financial markets. During the same time period that we examine, Ivashina et al. (2015) document how U.S. money market funds withdrew lending to Euro-area banks, and thus generated a foreign funding disadvantage for those banks. Due to the perceived deterioration in creditworthiness, the adverse shock for these banks lead to a spike in their dollar funding costs. While we focus on the real effect of a global bank borrowing from the US, our paper documents that the opposite side of this effect has been at work: perceived improvement in creditworthiness for some banks led to the increase in lending for them during the same period.

Our work is also related to recent studies in banking that highlight the importance of international transmission of policy shocks. Cetorelli and Goldberg (2012)) use bank level data from the U.S., and show that the banks with international subsidiaries are less sensitive to U.S. monetary policy.

Morais et al. (2019) use firm-bank level data and show that a softening of foreign monetary policy increases the supply of credit by foreign banks in Mexico. Ongena et al. (2011) use micro-level data and show that lower policy rates expand the supply of credit in the domestic currency, but not in foreign currencies. We differ from these papers in that rather than looking at policy shocks, we focus on a shock that is orthogonal to monetary policy.

The rest of the paper is organised as follows: Section 2 describes fundamentals of parity deviations. Section 3 and 4 describe data and methodology. Section 5 and 6 present micro- and macro-level results. Section 7 provides policy discussions, while section 8 concludes.

3.2 Deviatons from covered interest rate parity

Covered interest parity (CIP) is a central condition in finance, postulating that interest rates should be equal across currencies after accounting for the price of hedging exchange rate risk through an FX swap contract. For example, a bank with access to money markets around the globe can choose to obtain funding across a range of currencies. Suppose a European bank that needs to obtain EUR for a period of 3-months. It can for instance either obtain it in USD and enter an FX swap contract to hedge the exchange rate risk, or resort to direct funding in EUR. Letting F denote the FX (USD/EUR) forward price, S the FX spot price, i^f the unsecured funding cost in foreign currency (USD) and i^d the funding cost in domestic currency (EUR), the CIP conditions states that

$$\underbrace{\frac{F}{S}(1+i_f)}_{\text{Funding cost in foreign currency (USD), hedged for exchange rate risk}} = \underbrace{(1+i_d)}_{\text{Funding cost in domestic currency (EUR)}} \tag{3.1}$$

If the CIP does not hold, global lenders will obtain funds in the cheapest currency and enter an FX-swap contract to convert this funding to the currency of interest. Such lenders are then able to raise funds in the chosen currency at a lower price than they would pay in their home currency, and on better terms than their peers without access to foreign markets.

During the European Sovereign debt crisis, European banks were constrained in terms of U.S short-term funding (Ivashina et al., 2015). The shock affected primarily purely continental European banks. On the contrary, Norwegian and banks from other *safe-haven* countries experienced an increased supply of USD funding by US money market funds. This is illustrated in Figure 3.1, where we show the allocation of investments in commercial paper and certificates of deposits by U.S money market funds over time.[6] During the last months of 2011 the reduction of lending to Euro area banks was severe, even though the total worldwide investments made by U.S. money market funds did not change substantially.[7]

[6]U.S money market funds supply the majority of USD short-term funding to European banks.

[7]Figure 3.1 highlights how USD assets and liabilities of foreign banks have grown rapidly in the past two decades, and are currently above $10 trillion, which puts them roughly on par with U.S. banks. See also Ivashina et al. (2015).

–Insert Figure 3.1—

–Insert Figure 3.2 –

In Figure 3.2, we show the evolution of U.S money market funds' funding of Norwegian vs. continental European banks. The figure illustrates that, while there was a drop in funding to continental European banks, there was a contemporaneous increase in funding to Norwegian banks. Hence, in the midst of the crisis, high quality banks outside the Euro area obtained better access to money market funding. Norwegian banks were among those institutions that benefited from the reallocation of money market funds away from Euro-area banks.

The shift in the supply of funds gave internationally active Norwegian banks a substantial funding cost advantage compared to Norwegian banks not funding themselves in short-term USD funding markets. Norwegian banks with access to short-term funding in USD could obtain cheaper funding by exchanging USD for domestic currency and simultaneously hedging the FX risk compared to borrowing directly in NOK. Figure 3.3 illustrates this, by comparing the funding cost in NOK for hedged-USD funding with the cost faced by banks borrowing directly in NOK. At the height of the crisis, the funding cost advantage reached 150 bps. Such cost advantages were also present against other currencies, notably CAD, JPY, CHF, AUD. Figure 3.7 in the Appendix shows the strong relationship between favorable foreign funding for Canadian banks and borrowing: the outstanding volume of U.S. CD funding and CIP deviations correlate strongly with a correlation coefficient of 0.57.

–Insert Figure 3.3–

Not all Norwegian banks could exploit this cost-advantage. The Norwegian banking system comprises of a small number of high-rated globally oriented commercial banks with access to the U.S. commercial paper market. The remaining banks are relatively small domestic savings banks with no access to the U.S. money market. Access to U.S. money markets is effectively available only for large banks for two main reasons: first, money market funds require that at least one of the main rating agencies have a rating for the bank. Second, fixed costs make it worthwhile to issue commercial paper only if the amount raised is large. Because of these reasons, most smaller and medium sized Norwegian banks do not have access to short-term funding via the U.S. money markets.

As a result of this structure, the funding cost advantage documented in Figure 3.3 affected only the internationally active banks. A natural empirical strategy to isolate the effects of CIP deviations is therefore to compare the internationally active banks with other, domestic Norwegian banks. During the fall of 2011, the Eurozone-crisis escalated rapidly. As shown in Figure 3.3, this lead to a substantial decrease in the funding cost in foreign currency markets for Norwegian banks compared to the domestic banks. By the summer of 2012, most of the cost advantage had receeded to pre-2011 levels. In our main analysis, we therefore focus on how the increase the CIP funding advantage during 2011 and 2012 affected bank behavior.[8] We discuss our empirical strategy in more in detail in Section 3.4.

3.3 Data

In this section, we discuss the data used in our analysis. We start by describing the data soures, before discussing how we construct our final sample. Finally, we provide and discuss summary statistics of our final sample.

3.3.1 Description of data sources

[Description of data on how we construc the CIP-deviations]

In order to investigate the impact of covered interest parity deviations on bank lending and real economic outcome, we use data from three main sources: (1) a supervisory bank-level dataset, a (2) firm-level dataset from a credit rating agency and (3) an administrative loan-level dataset. Our bank data are obtained from several bank reports available at Norges Bank at a quarterly frequency. We take asset side variables (total asset size, liquid asset ratio) and liability side variables (foreign funding ratio) from the reports to construct our main set of bank-level outcomes variables, in addition to assign banks into a group of treated banks (banks operating in short-term international funding markets) and control banks (all other domestic banks). Our firm-level data consists of information on the end-of-year financial statements for all Norwegian private and public limited liability companies for the period 1997-2015. Norwegian companies are required to have an authorized auditor, and must file their annual financial statements after each accounting year. The accounting database includes the profit and loss account, the balance sheet, industry information and legal form. Finally, our loan-level dataset is an administrative data obtained from the Norwegian tax authorities. For tax reasons, all banks report all accounts on their books by the end of the year. A unit of observation in this data is therefore a loan between a bank and a firm. It contains firm and bank identifiers, as well as the outstanding loan balance and the interest paid over the calendar year.

3.3.2 Sample selection and data construction

We work with a subset of the combined three data sources. The subset is chosen based on two sets of criteria. First, we restrict attention to borrowers with positive debt, assets, sales and capital. Second,

[8]Table 3.11 in Appendix 3.8 shows that our results holds more generally, however.

in the firm-level regressions we exclude firms for which the dependent variable of the regression is below the 1st percentile or above the 99th percentile in the unconditional distribution of that variable.

In the case where firms have multiple loans at a specific bank, we aggregate our loan-level data to the relationship×year level.

Due to our focus on the Eurozone crisis, our final sample runs from 2009q1 to 2012q4.

3.3.3 Summary statistics

In this section, we show summary statistics at the bank- and firm-levels. We show separate summary statistics for treated vs. control banks, and firms borrowing from at least one treated banks vs. other firms.

–Insert Table 3.1–

Table 3.1 shows summary statistics at the bank-level, in addition to including the (aggregate) CIP funding deviation. Starting with the latter, the average CIP funding deviation is 29 bps, when we average commercial paper issuances at the quarterly level. That is, issuing funding abroad in an average quarter is 29 bps cheaper than issuing funding the NOK (with a standard deviation of 21 bps). Approximately 19% of the total liabilities of internationally active banks are short-term foreign funding, with a standard deviation of 10%. The table also compares treatment and control banks across several key ratios. Treated banks have slightly higher equity ratios, more liquid assets and are slightly larger compared to control banks.

Table 3.2 compares firm-level characteristics for firms that were served by at least one treated bank (treated firms) with those that were served only by control banks. Treated firms have more assets in place and pay higher wages. They have similar equity, R&D and short-term debt ratios.

–Insert Table 3.2–

3.4 Methodology

Our empirical approach consists of comparing bank-, loan- and firm-level outcomes based on whether banks were active in the short-term foreign funding market within a difference-in-differences setting, zooming in on the CIP shock of 2011 and 2012. We refer to the banks active in short-term foreign funding markets as "treated banks" and other banks as "control banks". We treat 2011 and 2012 as the "Post" period and 2009 and 2010 as the pre-period.

In our empirical strategy, we rely on two identifying assumptions which are akin to the standard parallel trends assumption in a difference-in-differences set-up. Specifically, Assumption 3.4 assumes parallel trends at the bank- and loan-level while Assumption 3.4 assumes parallel trends at the firm-level.

The outcomes considered at the bank- and loan-level would have been similar for treated and control banks in the absence of the CIP-shock.

We refer to firms borrowing from at least one treated bank in the year prior to the shock as a "treated firms" and other firms as "control firms".

The outcomes considered at the firm-level would have been similar for treated and control firms in the absence of the CIP-shock.

There are at least two main threats to these identifying assumptions. The first threat is that outcomes are systematically different for treated and control banks at the bank- and loan-level, and systematically different for treated and control firms at the firm-level. This can arise for instance if treated banks over the time-period considered have different business models compared to our control banks giving rise to differential corporate credit growth.

We address this threat to identification by adopting a dynamic difference-in-differences approach, where we explicitly test for differences between treated and control units also prior to the shock. At the bank-level, this is our baseline regression. At the loan- and firm-level, where our data has an annual frequency, our baseline regression is a static difference-in-differences. We report the results from dynamic difference-in-differences in the appendix.

Our second main threat to identification is that, even if treated and control banks and firms are similar prior to the shock, they may be hit by different shocks during the treatment period. For instance, this can be the case if treated banks are more exposed to Eurozone credit markets, or if treated firms are more likely to be exporting firms, and thereby be more affected by the slowdown in the Eurozone economy.

We adopt two strategies to rule out such confounding demand and supply shocks. First, at the loan-level we adopt an approach a la Khwaja and Mian (2008), effectively only using variation within firm-year. Second, at the firm-level we only use within-industry×year×size variation, which ensures that we compare outcomes for relatively similar firms borrowing from different types of banks.

Conditional on these identifying assumptions being satisfied, our estimates map out the effect of the CIP shock onto bank funding and lending decisions, the effect at the loan-level and ultimately how the CIP shock translate into differential real economic outcomes.

In the rest of this section, we explicitly outline how we operationalize our identification strategy at the different units of analysis.

Bank-level At the bank-level, we estimate equation (3.2)

$$\Delta Y_{b,t} = \alpha_b + \sum_{\tau} \delta_\tau \mathbf{1}_{t=\tau} + \sum_{\tau} \gamma_\tau \left(D_b \times \mathbf{1}_{t=\tau} \right) + \epsilon_{b,t} \tag{3.2}$$

where b refers to bank and t to time. The outcome variable $\Delta Y_{b,t}$ denotes the change in either foreign currency denominated short-term funding or the change in log(corporate loans). The treatment indicator D_b is equal to 1 if a bank has positive short-term foreign funding in 2011q2. At the bank-level, $D_b = 1$ for approximately 12 % of banks.

Loan-level At the loan-level, we estimate

$$\Delta Y_{b,f,t} = \alpha_b + \alpha_{f,t} + \sum_{\tau} \delta_{\tau} \mathbf{1}_{t=\tau} + \sum_{\tau} \gamma_{\tau} \left(D_b \times \mathbf{1}_{t=\tau} \right) + \epsilon_{b,f,t} \tag{3.3}$$

where f refers to firm. The main outcome variable is growth at the loan-level. We saturate our specification with bank fixed effects. In addition, we include firm×year fixed effects captured by $\alpha_{f,t}$ for the subsample of loans at firms that borrow from multiple banks (Khwaja and Mian, 2008). This subsample constitutes roughly 10% of the sample of loans. At the loan-level, $D_b = 1$ for approximately 74 % of our sample.

Firm-level At the firm-level, we estimate

$$\Delta Y_{f,t} = \alpha_f + \mathbf{1}_{t=2011 \cup t=2012} + \gamma \left(\mathbf{1}_{t=2011 \cup t=2012} \times D_b \right) + \mathbf{X_{f,t}} + \epsilon_{f,t} \tag{3.4}$$

where $\Delta Y_{f,t}$ is chosen from a broad set of firm balance sheet and income statement variables. To control for confounding factors, we include firm-year controls $\mathbf{X_{f,t}}$. Specifically, we control for year×industry×fixed effects.

3.5 Micro-level response

In this section, we go through the different levels of analysis at the micro-level. We start by investigating the impact of the shock to growth in short-term foreign funding and overall corporate credit for treated banks, and show that both variables increase at the time of the shock. We then move to a loan-level analysis, and show that treated banks expand credit relative to control firms, after controlling for firm × fixed effects. We then investigate how a range of firm outcomes are affected. We show that treated firms increase dividend payouts and take on more debt. They also expand production and investment into fixed assets. The investment into fixed assets is driven both by an increase in financial fixed assets and an increase in capital investment.

3.5.1 Bank-level

– Insert Figure 3.4

In Figure 3.4 we show the evolution of the level of aggregate foreign funding for treatment and control banks over time. The evolution is relatively flat for both groups of banks prior to 2011q3.

In 2011q3 however, there is a substantial increase in the level of foreign funding for treatment bank which persists throughout the remainder of the sample. The third quarter of 2011 correspond to the beginning of the escalation of the Eurozone crisis, and also the point in time for when the USD cost advantage started to become especially pronounced (Figure 3.3.) Overall, the timing is consistent with the USD cost advantage leading to increased foreign borrowing by the affected banks.

To shed further light on this, we move on to estimate equation 3.2 using the share of foreign funding to total assets as dependent variable. For each period, we estimate the difference in *total* foreign funding to total assets for treated and control banks.[9] The time-varying differences between treated and control banks are shown in Figure 3.5.

–Insert Figure 3.5

Conditional on group fixed effects, the fraction of foreign funding to total assets evolves relatively similar for treated and control banks for all periods considered, except the third and fourth quarter of 2011 where there is a sizable and significant increase in foreign funding at the treated banks. The difference is large. In 2011q3 and 2011q4, foreign funding relative to total assets is approximately 3 %-points higher for the treatment group. Once the shock reverts. This finding is consistent with the USD cost advantage shock leading treated banks to increase their intake of short-term foreign funding.

Next, we examine what happens to the corporate credit share at the bank-level. In Figure 3.6, we show the time-varying differences in the share of corporate loans to total assets for treated and control banks.

–Insert Figure 3.6

While the difference between the two groups are a bit noisier compared to the previous figure, there are no significant differences in the corporate credit share between treated and control banks prior to the shock. After the shock, there is an uptick in corporate credit for treated banks. For 2011q4, the difference in corporate credit relative to total assets between treated and control banks is approximately 2 %-points. This is consistent with the relative increase in foreign funding documented in Figure 3.5, which translated into higher credit supplied to corporations.[10]

A potential challenge to our bank-level analysis is that the difference in corporate credit growth between treated and control banks may be driven by other factors, such as confounding demand shocks. We therefore proceed to investigate whether the observed increase in corporate credit at the bank-level is also present at the loan-level in a setting in which we can control for time-varying factors affecting credit demand.

[9] Both treated and control banks are active in more long-term foreign funding markets through issuance of covered bonds in especially Euro.

[10] In the Online Appendix, we show that the remainder of the foreign funding acquired in 2011q3 and 2011q4 is deposited at foreign central banks.

3.5.2 Loan-level

In this section, we explore whether the observed increase in corporate credit is present at the loan-level. Using loan-level data allows us to further substantiate that we are identifying a credit supply expansion by (1) investigating both quantity and price responses and (2) control for firm-specific factors. Our baseline loan-level results are given in Table 3.3.

–Insert Table 3.3–

Starting with column (1), loan-level credit growth is approximately 3.2% higher on loans from treated banks compared to control banks. The economic magnitude is relatively large. Specifically, the unconditional mean credit growth is -6.8%. Put differently, the effect on loan-level credit growth from borrowing from a treated bank is almost 50 % of the absolute value of average credit growth. In columns (2) and (3), we restrict attention to the sample of firms borrowing from more than one bank, and where at least one of those banks is treated. This represents approximately 10% of our sample. In column (2), we run our baseline regression *without* firm× year fixed effects, whereas the results from our referred specification with firm×year fixed effects is given in column (3). The results in column (3) indicate that credit growth within a firm×is approximately 6% higher at treated banks. Again, compared to a mean credit growth of -10.5%, these results suggest that there is a sizable expansion in credit at the loan-level for loans from treated banks compared to control banks.

In Table 3.4 we repeat the estimation, using the change in interest paid relative to outstanding debt as dependent variable. Consistent with a credit supply shocks, there is a significant decline in loan-level interest rates once we control for firm-specific factors in Column (3).

–Insert Table 3.4–

From the previous tables, it remains unclear whether the expansion in credit is equally spread across all firms in the economy. To examine the heterogeneity of the effects across firms, in Table 3.5 we repeat the loan-level estimation in Column (1) of Table 3.3 interacting the treatment × shock-period variable with a broad range of firm-characteristics. Over a broad set firm characteristics, only the export-dummy has a statistically significant impact on our estimate. The coefficient estimate suggests that exporting firms have a significantly higher loan-level credit growth following the shock. A potential explanation for this can be that they during the sovereign debt crisis had a more elastic demand for bank debt and hence were more likely to utilize the increase in bank debt. Note that in Tables 3.3 3.4 we do include firm× year factors, suggesting that *within* an exporting firm there is an increase in credit and a decrease in price.

–Insert Table 3.5–

3.5.3 Firm-level

Next, we examine the impact of the USD cost advantage shock at the firm-level. We start by looking at a range of firm outcomes in Table 3.6.

–Insert Table 3.6–

In column (1), we consider the growth in bank debt as dependent variable. The column shows that there is a statistically significant increase in bank debt at the firm level, even though it is somewhat smaller as compared to that observed at the loan-level. Column (2) shows the results from a regression using log(sales) as a dependent variable. There is a positive and statistically significant effect on sales for treated firms. The magnitudes are large: the estimated impact is 2.7%, compared to an unconditional mean of 3.6%. In column (3), we show that there is a positive and statistical effect on the change in wages. In column (4), we show a statistically significant impact on the growth in fixed assets. The effects are large, and roughly equal to the mean growth in fixed assets. In column (5), we do not find a similar impact on current assets. Therefore, the expansion in credit that comes from increased *short-term* funding at banks translates into *long-term* investment at the firm-level.

–Insert Table 3.7–

In Table 3.7, we provide further evidence of how treated firms adjust their capital structure in response to the shock. Importantly, we find that firms increase their leverage. While the expansion in credit does not lead to more dividends (extensive margin) (column 1), firms increase dividend payouts (intensive margin) (column 2). As there is no expansion in equity (column 3) - suggesting that any increased profits is paid out rather than retained -, firms expand their overall debt (column 4). This suggests that the expansion of bank credit does not replace other forms of credit. Rather it leads to an increase in debt. The increase in debt occurs via both an increase in short-term and long-term debt, as highlighted in columns (5) and (6).

Explaining the effect on fixed assets

Next, we exploit the granularity of our firm-level data to examine the type of fixed assets that firms invest in. In our database, fixed assets consist of three sub-components: fixed financial assets, capital and intangible assets. The overall impact of the credit supply expansion on the real economy is likely to depend substantially on whether firms allocate surplus funds to financial investments, whether they invest in intangible assets, or whether the credit supply expansion leads to more capital investment. In Table 3.8, we replicate our estimation, while focusing on the different components of fixed assets.

–Insert Table 3.8–

In Column (1), we reproduce Column (6) from Table 3.6. Columns (2) - (4) report the results from using the different subcategories of fixed assets as outcome variables. In column (2), we show that there is a positive and statistically significant impact on financial fixed assets. This comprises intra-conglomerate holdings of other firms, as well as investments in publicly listed stocks and bonds. In column (3), we show that there is also an increase in capital investment for treated firms. Treated firms have approximately a 1.25% higher growth in capital as compared to control firms. This is roughly equal to the absolute value of the unconditional mean of capital growth, suggesting that the relative large increase in bank credit translates to a relatively large increase in capital.

Heterogeneous effects

Given that we observed a larger credit growth for exporting firms, a natural question is whether they are crucial for driving the capital response documented in Table 3.6. In order to do so, we redo our firm-level estimation including a wide range of firm-characteristics as interaction terms. We restrict attention to focusing on the impact on capital. The results are reported in Table 3.9. Consistent with our loan-level results, exporting firms have significantly higher capital growth.

3.6 Macro-level response

In the previous section, we documented that the increase in lending at the bank- and loan-level, translated to higher growth in sales and capital at the firm-level. In this section, we provide back-of-the-envelope calculations on how important these effects were for the *aggregate* growth in sales and capital. In order to do so, we aggregate our estimates in Tale 3.6 using lagged sales or capital as weights. Our analysis implicitly relies on two assumptions (see for instance Chodorow-Reich 2014): there are no general equilibrium effects; and in the absence of the shock, sales/capital would have had a growth rate equal to the average growth rate of control firms. The results of our aggregation exercise are shown in Table 3.10

–Insert Table 3.10–

Both in 2011 and 2012, the growth in sales and capital is substantially higher as compared to our aggregated series in the counterfactual case. Specifically, the sales growth is 5% higher in 2011 *due to* the CIP shock and 1.2% higher in 2012. Capital is 1% higher in 2011 and 2.9% higher in 2012. This suggests that the CIP shock not only translated into a relatively large increase in domestic lending, but also into a substantial increase in both sales and capital at the aggregate level.

3.7 Policy implications

The issue of refinancing risk has been a topic of core discussions in both academic and policy circles. Short-term foreign funding represents high refinancing risk, especially due to the fact that generally, and in our setting in particular, this consists of *unsecured* commercial paper and certificate of deposits. Precisely due to its unsecured nature, this type of funding is likely to dry up in bad times, as it happened in the Great Financial Crisis around the world, or in Euro area banks during the European sovereign debt crisis. Norwegian policymakers, too, have expressed their concern regarding the matter:

"This funding comprises short-term paper and deposits from money market funds and large companies. Deposits can be withdrawn quickly and are not considered stable. Short-term money market funding is considered unstable owing to short maturities."(Norges Bank Financial Stability Report, 2018).

As Diamond and He (2014) point out, such pro-cyclicality is further exacerbated due to a possible debt overhang with short-term debt. The value of short-term debt is not very sensitive to new investment. This may create little value transfer from investment to debtholders, and ameliorate debt overhang (underinvestment as in Myers (1977)). Yet, due to this insensitivity in the long-run, it becomes problematic in volatile periods and in bad times, as equity value becomes highly volatile: highly volatile equity means more state-contingent scenarios of potential underinvestment, and debt-overhang will increase. Therefore, policies of lengthening debt maturity in the times of crisis can have positive effects on bank lending and real activity.

Despite the CIP shock being orthogonal to monetary policy, it has implications for monetary authorities. Banks' private incentives to borrow short-term may lead individual banks to overdo so. This is because banks do not fully internalize potential fire-sales costs to which their maturity transformation activities will lead (Stein, 2012). In a crisis, the only way for banks to honor their short-term debt would be to sell their long-term assets at fire-sale prices. The potential for such fire sales may give rise to a negative externality. Thus, unregulated banks may engage in excessive short-term borrowing leaving the financial system overly vulnerable to costly crises. However, if banks' short-term liabilities are subject to reserve requirements, the monetary policy can be used as a mechanism: the central bank can inject or contract reserves into the system, effectively changing the amount available for lending amount. Therefore, policymakers are better off expanding regulation (e.g. reserve requirement, or haircut) on such short-term facilities. This is especially true when there is no other direct impact on the schedule of foreign funding availability, such as pricing which can be altered only for local borrowing. [11]

[11] Kashyap and Stein (2000) describe monetary policy shocks in the U.S. prior to the financial crisis, as it worked through funding availability. As they convincingly argue, credit supply may be affected by monetary policy through changing central bank reserves available to the banking system. Under these circumstances, such monetary policy would work only if the bank cannot substitute the drained reserved by other, non-reservable funding such as certificate of deposits. The effect of reserves on funding availability in this system is over and above the effect of the changes in reserves on interest rates (which used to be the case also in the previous U.S. monetary system). This monetary

Thus, the short-term nature of the shock puts it apart from academic and policy discussions on longer term refinancing. For instance, the 2011 European Central Bank's (ECB) long-term refinancing operations (LTRO) allowed participating banks get unlimited funding of long-term (three-year) maturity at similar conditions as in case of the short-term borrowing (the same interest rate, pool of eligible securities and haircut policy). At the time of the ECB policy decision, Euro area banks were relying on short-term debt and were largely exposed to rollover risk. The purpose of the LTRO policy was, by ensuring stable funding for a horizon of three years, the substantially lengthened maturity of bank liabilities and sizably reduced uncertainty about the refinancing conditions over a longer period would support bank investment. While this may imply that short-term financing may not have credit or, more importantly, real implications, we show the opposite.

3.8 Conclusions

In this paper, we take an empirical approach to investigate the impact of a shock to short-term funding in a subset of Norwegian banks during the European sovereign debt crisis of 2011. During this event, internationally active Norwegian banks could benefit from their access to USD-denominated debt markets. Because of deviations in the covered interest parity, once translated into Norwegian Krone USD-denominated debt allowed internationally active Norwegian banks to obtain favourable funding terms as compared to other Norwegian banks that only had access to domestic funding.

The asymmetric nature of this shock gives us the opportunity to examine how a shock to short-term funding, that is unrelated to domestic monetary policy, affects lending behaviour of banks with different exposure to the shock. By making use of a supervisory bank-level dataset, in conjunction with loan- and firm-level data, we can quantify the effects of the shock in the cross-section of firms in the economy. The completeness of our data allows us to control for firm demand by employing a granular set of fixed effects.

We find that firms that borrowed from internationally active banks benefited from an expansion in credit, and this effect was stronger for firms with multiple banking relationships. The effect was not limited to quantities but also extended to prices. Our results indicate that the favorable foreign funding shock to bank financing translated into an expansion of domestic credit. We also show that despite the short-term nature of the shock, firm borrowing was employed to support long-term investment more than to prop up short-term assets. Finally, we find that the shock had a significant aggregate impact on the Norwegian economy.

system used to be the case in the U.S. before, while nowadays the amount of central bank reserves available to the banking system is decoupled from the monetary policy stance. Our shock originates abroad, and is not related to monetary policy.

Figures and Tables

Figure 3.1
Investment by U.S. prime money market funds across regions

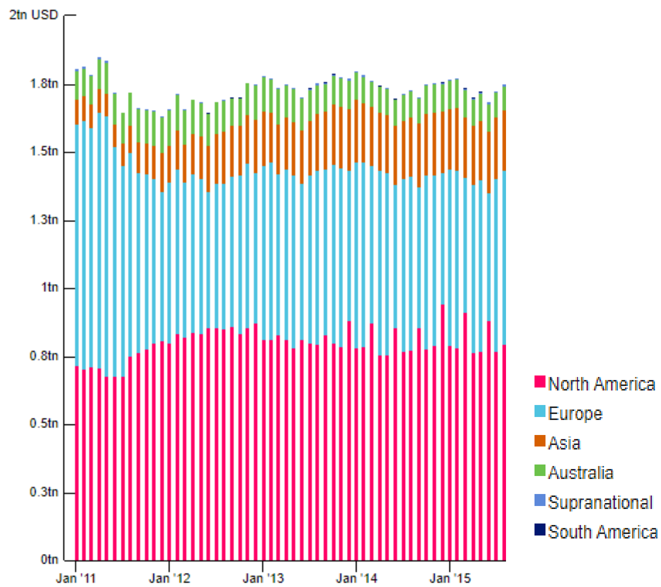
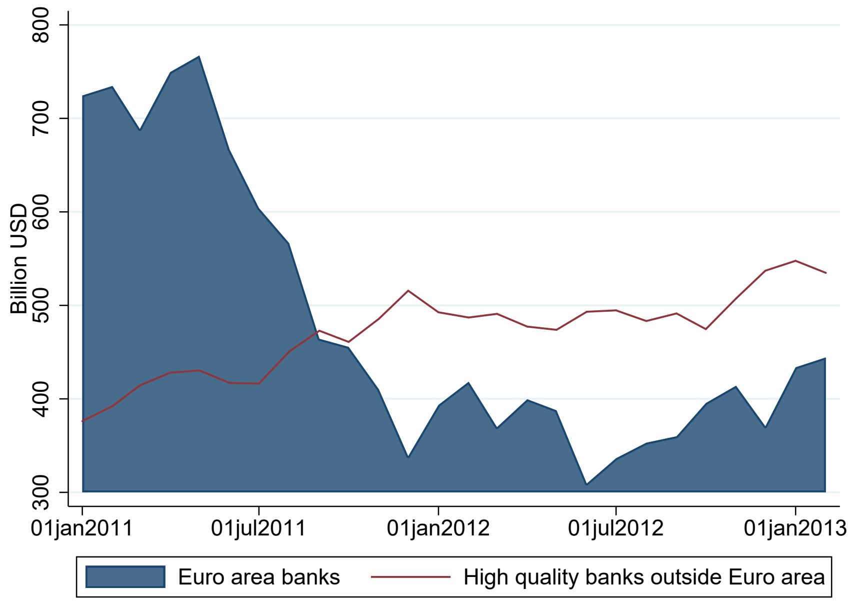


Figure 3.2
Investment by U.S. prime money market funds in safe heavens , as compared to main Euro area countries.

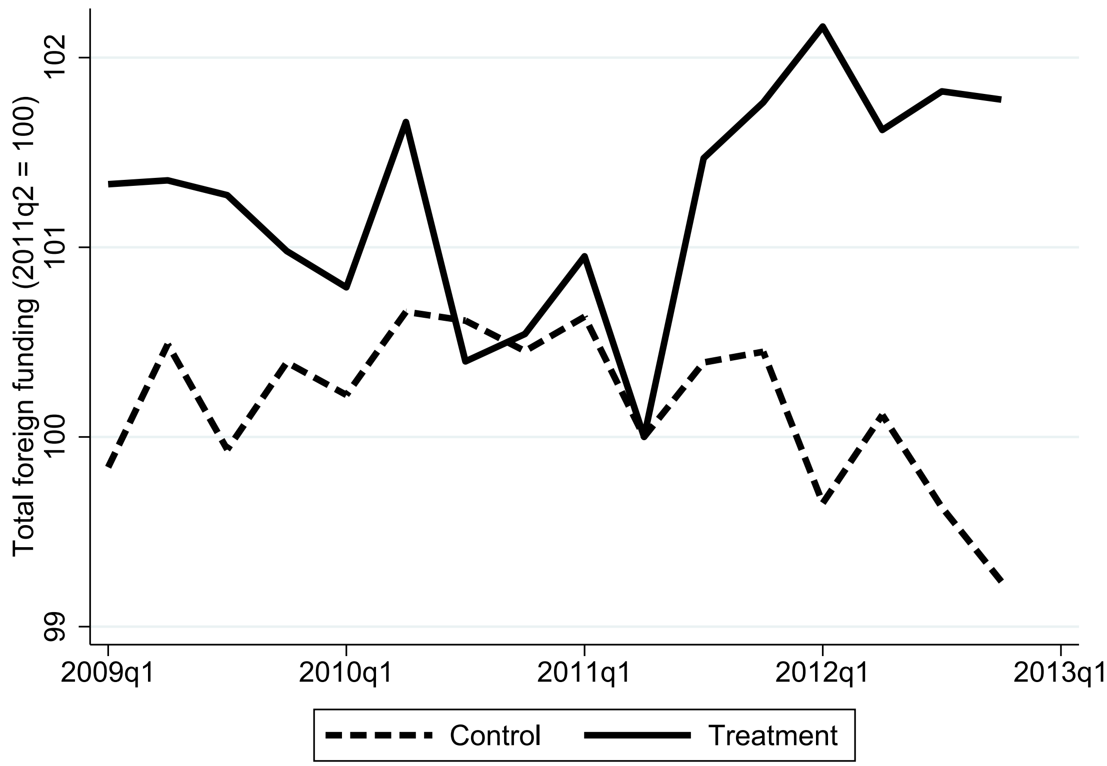


Notes: Safe havens defined as Australia, Canada, Denmark, Norway, Sweden, Switzerland, while the main Euro Area countries consists of Austria, Belgium, Finland, France, Germany, Ireland, Italy, Luxembourg, the Netherlands, Spain

Figure 3.3
CIP funding deviations for Norwegian banks

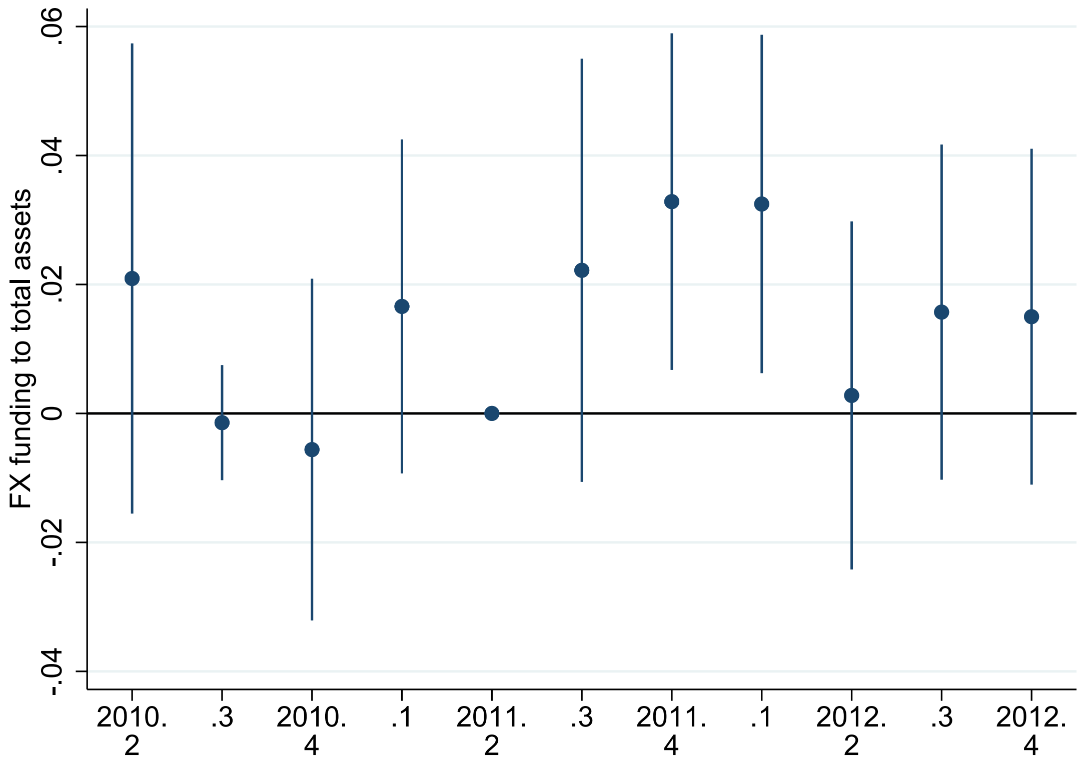
Notes: A negative value indicates cheaper USD hedged funding as compared to domestic borrowing in NOK.

Figure 3.4
Evolution of foreign funding, treatment and control.



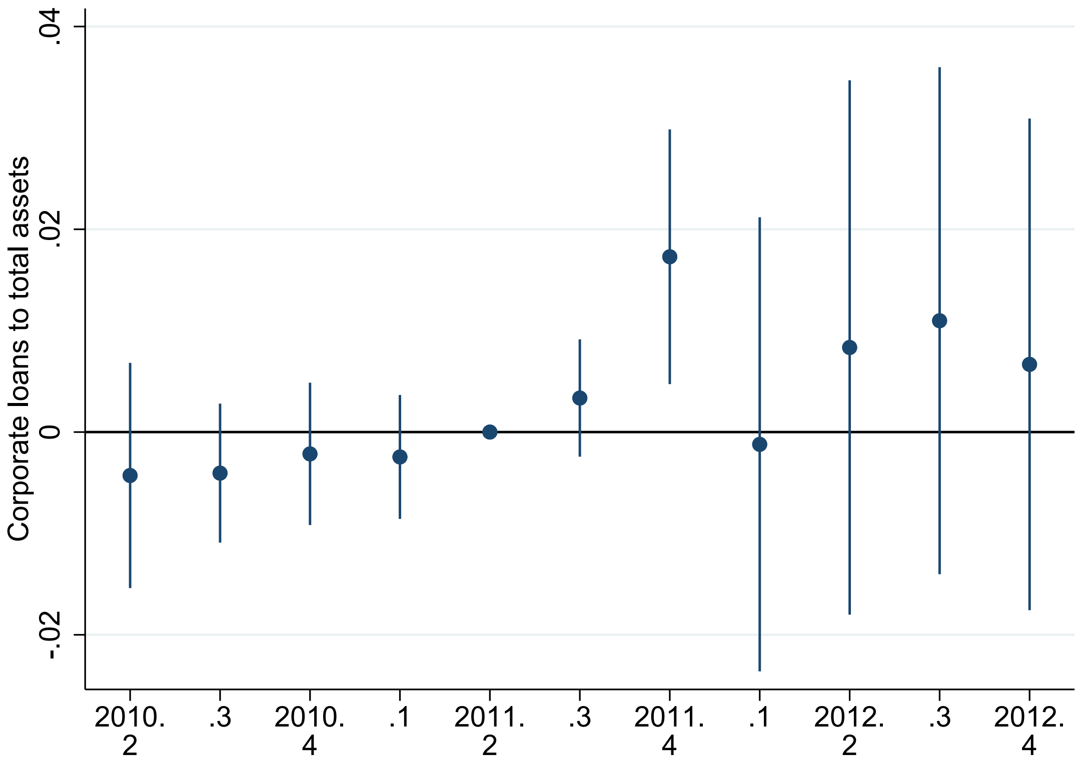
Notes: This figure shows the evolution of aggregate foreign funding for treatment and control banks. To facilitate comparison, we have indexed each series where 2011q2 is set as base quarter.

Figure 3.5
Relative growth in foreign funding (treated banks)



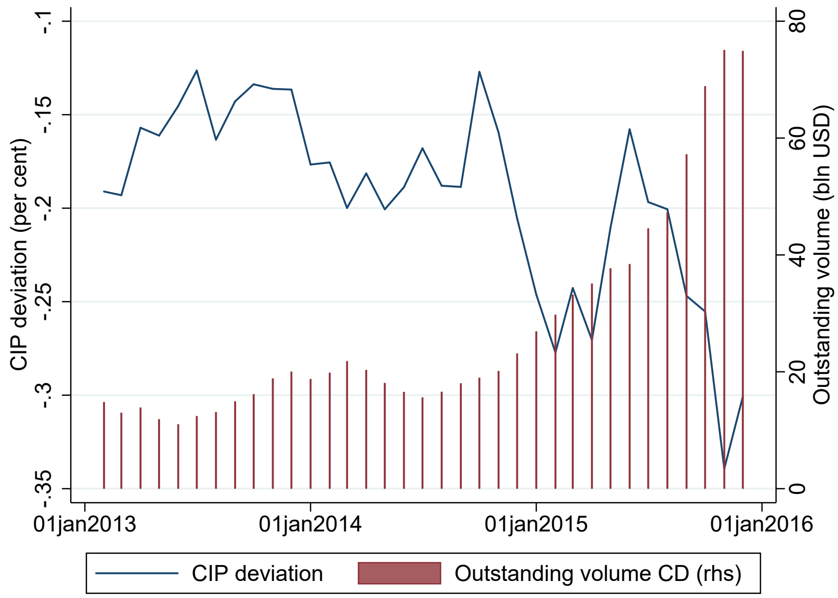
Notes: This figure shows the estimated γ_τ from equation (3.2) using the foreign funding relative to total assets as outcome variable. Dots indicate point estimates and vertical lines are the associated 95% confidence interval. All coefficients are plotted relative to 2011q2.

Figure 3.6
Relative growth in corporate lending (treated banks)



Notes: This figure shows the estimated γ_τ from equation (3.2) using corporate loans to total assets as dependent variable. Dots indicate point estimates and vertical lines are the associated 95% confidence interval. All coefficients are plotted relative to 2011q2.

Figure 3.7
CIP funding deviations USD/CAD



Notes: This figure shows the evolution of CIP funding deviations between USD and CAD (blue line, left axis) and the outstanding volume of USD funding (orange line, right axis) . Negative figures indicate cheaper USD hedged funding compared to CAD.

Table 3.1
Summary statistics, bank-level

	(1)		(2)		
	Control		**Treatment**		**Difference** (Control - Treatment)
	Mean	Std. dev	Mean	Std. dev	
CIP funding deviation			-0.29	0.21	
Short-term foreign fund ratio			0.19	0.10	
Equity / Assets	0.04	0.02	0.06	0.04	-0.011***
Deposits / Assets	0.62	0.13	0.62	0.22	0.005
Liquid assets / Assets	0.10	0.09	0.18	0.18	-0.08***
Log(Assets)	10.99	1.28	11.77	1.81	-0.78**
Observations	117		23		

Notes: This table report summary statistics at the bank-level. All values based on end of 2010 balance-sheet statement. Summary statistics are computed for banks active in international short-term funding market ("Treated", column (2)) and other banks ("Control", column (1)). *** indicates $p < 0.01$ and ** indicates $p < 0.05$, where p is the p-value on a test of equality across groups.

Table 3.2
Summary statistics, firm-level

	(1)		(2)		
	Control		**Treatment**		**Difference** (Control - Treatment)
	Mean	Std. dev	Mean	Std. dev	
log(Wages)	6.99	1.90	7.23	1.96	-0.23***
log(Capital)	7.26	1.86	7.81	2.14	-0.55***
log(Assets)	8.33	1.32	8.82	1.62	-0.48***
Cash / Assets	.13	.17	.12	.16	0.01***
Equity / Assets	.28	.20	.29	.29	-0.01***
Short-term debt / Assets	0.32	0.26	0.31	0.25	0.01***
R&D and patents / Assets	0.001	.02	.002	.03	-0.001***
Exporter	0.02	0.17	0.03	0.17	-0.01***
Observations	13'925		30'667		

Notes: This table report summary statistics at the firm-level. All values based on end of 2010 income and balance-sheet statement. Summary statistics are computed for firms borrowing from treated banks ("Treated", column (2)) and other firms ("Control", column (1)). *** indicates $p < 0.01$, where p is the p-value on a test of equality across groups. Short-term is debt with maturity less than 12 months. Exporter is a dummy variable indicating whether the firm belongs to an exporting industry, defined as the 10 most exporting industries based on aggregate input-output tables.

Table 3.3
Loan-level results

	(1) Growth in debt	(2) Growth in debt	(3) Growth in debt
$D_b \times$Post	0.0321**	0.0402	0.0605**
	(0.0127)	(0.0282)	(0.0305)
N	162315	15745	15745
No. of clusters	111	110	110
Mean of dependent variable	-0.0687	-0.105	-0.105
SD of dependent variable	0.627	0.716	0.716
Bank FE	Yes	Yes	Yes
Firm FE	Yes	Yes	No
Firm-Year	No	No	Yes
Sample	All	Multiple banks	Multiple banks
R-squared	0.00356	0.0108	0.484

Notes: This table contains the results from estimating equation (3.4) using loan-level credit growth as outcome variable. * $p<0.1$, ** $p<0.05$, ***$p<0.01$. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Column (1) considers the full sample. Columns (2) and (3) consider only firms borrowing from at least one internationally active and one internationally non-active bank. Standard errors two-way clustered at the bank-firm level.

Table 3.4
Loan-level results, interest rates

	(1)	(2)	(3)
	ΔInterest rate	ΔInterest rate	ΔInterest rate
$D_b \times$Post	0.00184	-0.00802	-0.0146**
	(0.00216)	(0.00615)	(0.00640)
N	143605	12383	12383
No. of clusters	111	110	110
Mean of dependent variable	0.000420	0.00134	0.00134
SD of dependent variable	0.157	0.176	0.176
Bank FE	Yes	Yes	Yes
Firm FE	Yes	Yes	No
Firm-Year	No	No	Yes
Sample	All	Multiple banks	Multiple banks
R-squared	0.0852	0.0790	0.502

Notes: This table contains the results from estimating equation (3.4) using imputed interest rates as outcome variable. * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Column (1) considers the full sample. Columns (2) and (3) consider only firms borrowing from at least one internationally active and one internationally non-active bank. Standard errors two-way clustered at the bank-firm level.

Table 3.5
Loan-level results - heterogeneity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Growth in debt	Growth in debt	Growth in debt	Growth in debt	Growth in debt	Growth in debt	Growth in debt	Growth in debt
D_b×Post	0.0741**	0.0580	0.0671**	0.0470	0.0162	0.0783**	0.0529	0.0177
	(0.0343)	(0.0774)	(0.0305)	(0.0593)	(0.0427)	(0.0312)	(0.0512)	(0.0577)
D_b×Post×Low TFP, 2010	0.00192							
	(0.0512)							
D_b×Post×Top rating, 2010		0.0190						
		(0.0934)						
D_b×Post×Exporter, 2010			0.393*					
			(0.209)					
D_b×Post×Large, 2010				0.0396				
				(0.0611)				
D_b×Post×Cash / Total assets, 2010					0.243			
					(0.154)			
D_b×Post×Net income / Total assets, 2010						-0.00513		
						(0.00842)		
D_b×Post×Equity / Total assets, 2010							0.0864	
							(0.157)	
D_b×Post×Short-term debt / Total assets, 2010								0.147
								(0.147)
N	14726	14726	14726	14726	15745	14211	14722	14722
No. of clusters	110	110	110	110	110	110	110	110
Mean of dependent variable	-0.102	-0.102	-0.102	-0.102	-0.105	-0.103	-0.102	-0.102
SD of dependent variable	0.713	0.713	0.713	0.713	0.716	0.715	0.712	0.712
Bank FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table contains the result from estimating equation (3.4), using loan-level credit growth as outcome variable and where we add a triple interaction term based on firm-characteristics. Low TFP is defined as a dummy variable equal to 1 if the firm had an estimated TFP below the industry median in 2010. TFP is estimated by regressing log value added on the wage bill, firm capital, as well as year, firm and industry fixed effects. * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Standard errors are two-way clustered at the bank-firm level.

Table 3.6
Firm-level results

	(1)	(2)	(3)	(4)	(5)
	Growth in bank debt	ΔLog(sales)	ΔLog(wages)	ΔLog(Fixed Assets)	ΔLog(Current assets)
$D_b \times$Post	0.0233**	0.0276***	0.0116*	0.0130**	-0.00775
	(0.0115)	(0.00595)	(0.00673)	(0.00498)	(0.00848)
N	126053	79119	76465	112427	115235
No. of clusters	109	108	108	108	108
Mean of dependent variable	-0.0620	0.0359	0.0518	0.0118	0.0393
SD of dependent variable	0.578	0.365	0.342	0.345	0.583
Firm FE	Yes	Yes	Yes	Yes	Yes
Year-Industry FE	Yes	Yes	Yes	Yes	Yes

Notes: This table contains the results from estimating equation (3.4) using different firm outcomes as dependent variable across columns. * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Standard errors are two-way clustered at the bank-firm level. Dependent variables are truncated at the 1st and 99th percentile.

Table 3.7
Firm-level results

	(1) Dividends>0	(2) ΔLog(dividends)	(3) ΔLog(Equity)	(4) ΔLog(debt)	(5) ΔLog(short-term debt)	(6) ΔLog(long-term debt)
$D_b \times$Post	-0.0000833	0.233**	0.00818	0.0207*	0.0113*	0.0121*
	(0.00347)	(0.100)	(0.00758)	(0.0119)	(0.00576)	(0.00624)
N	151257	16698	116077	115973	104260	105337
No. of clusters	109	107	108	108	108	108
Mean of dependent variable	0.171	1.225	0.0859	-0.0674	0.0415	-0.0642
SD of dependent variable	0.377	2.379	0.429	0.676	0.412	0.432
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year-Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table contains the results from estimating equation (3.4) using different firm outcomes as dependent variable across columns. * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Standard errors are two-way clustered at the bank-firm level. Dependent variables are truncated at the 1st and 99th percentile.

Table 3.8
Firm-level results, decomposing the effect on fixed assets

	(1)	(2)	(3)	(4)
	ΔLog(Fixed Assets)	ΔLog(Financial asssets)	ΔLog(Capital)	ΔLog(Intangibles)
$D_b\times$Post	0.0130**	0.0326**	0.0116*	0.0147
	(0.00498)	(0.0147)	(0.00595)	(0.0203)
N	112427	52628	102341	33512
No. of clusters	108	108	108	108
Mean of dependent variable	0.0118	0.0338	-0.0163	0.0534
SD of dependent variable	0.345	0.617	0.370	0.685
Firm FE	Yes	Yes	Yes	Yes
Year-Industry FE	Yes	Yes	Yes	Yes

Notes: * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Standard errors two-way clustered at the bank-firm level. Dependent variables are truncated at the 1st and 99th percentile.

Table 3.9
Firm-level results, heterogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
	ΔLog(Fixed Assets)	ΔLog(Fixed Assets)	ΔLog(Fixed Assets)	ΔLog(Fixed Assets)	ΔLog(Fixed Assets)	ΔLog(Fixed Assets)
D_b×Post	0.0130**	0.0117*	0.00386	0.0203**	0.0337**	0.0114**
	(0.00498)	(0.00665)	(0.00989)	(0.00855)	(0.0142)	(0.00516)
D_b×Post×Large, 2010		0.00966				
		(0.00844)				
D_b×Post×Equity / Assets, 2010			0.0272			
			(0.0304)			
D_b×Post×Cash / Assets, 2010				-0.0353		
				(0.0402)		
D_b×Post×Top rating, 2010					-0.0238*	
					(0.0141)	
D_b×Post×Exporter, 2010						0.0645**
						(0.0325)
N	112427	111129	111127	112427	111129	111129
No. of clusters	108	108	108	108	108	108
Mean of dependent variable	0.0118	0.0119	0.0119	0.0118	0.0119	0.0119
SD of dependent variable	0.345	0.345	0.345	0.345	0.345	0.345
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year-Industry FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2009 - 2012). Post = 1 for 2011 and 2012, and zero otherwise. Standard errors two-way clustered at the bank-firm level. Dependent variables are truncated at the 1st and 99th percentile.

Table 3.10
Aggregate implications for growth in capital and sales

	Sales		**Capital**	
	Actual	Counterfactual	Actual	Counterfactual
2011	11.4%	6.4%	1.8%	0.8%
2012	2.7%	1.5%	4.2%	1.3%

Notes: This table contains counterfactual aggregate sales and credit growth. Counterfactual growth measures are computed based on the procedure in section 3.6.

Table 3.11
Robustness - panel regression

	(1)	(2)
	ΔLog(foreign funding)	ΔLog(corporate loans)
$CIP_t \times D_{b,2011q2}$	0.298*	0.00209**
	(0.153)	(0.000960)
N	475	2719
Mean of dependent variable	-0.014	-0.000149
SD of dependent variable	0.406	0.00573
Bank FE	Yes	Yes
Year FE	No	No
R-squared	0.0483	0.0382

Notes: * p<0.1, ** p<0.05, ***p<0.01. Mean and standard deviations are taken over the full sample period (2010 - 2015). CIP is normalized, so that a positive value indicates more favorable foreign funding conditions. Column (1) considers the change in the log of foreign liabilities as dependent variable. Column (2) considers the change in the log of corporate loans as dependent variables. Standard errors clustered at the bank-level.

Chapter 4

Covered Interest Parity in long-dated securities

4.1 Introduction

Covered Interest Parity (CIP) has been known as one of the most reliable no-arbitrage conditions in international finance. According to CIP it should not be possible to earn risk free profit by borrowing in one currency and investing in another with the foreign exchange rate fully covered. Since the global financial crisis (2008-2009), seemingly large deviations from CIP have puzzled academics, policy makers and market participants alike. Despite several years of tranquil financial conditions, recent work indicates persistent and sizeable arbitrage opportunities in some of the most liquid long-dated fixed income and currency markets in the world (Du et al. (2019), Liao (2020), Sushko et al. (2016), Avdjiev et al. (2019)).

The failure of CIP is commonly ascribed to the post-crisis tightening of banking regulations.[1][2] According to this view, tighter balance sheet constraints make it more costly for banks to step in as arbitrageurs. In turn, this may lead to unexploited arbitrage opportunities, less efficient markets and a breakdown of CIP. If proven correct, stricter banking regulations have broad implications for market efficiency and the relative pricing of fixed income securities across currencies.

This paper revisits the validity of CIP across a range of long-dated fixed income securities for three major currency pairs; EUR, JPY and GBP, against USD.[3] An important premise for CIP arbitrage is that the profit is riskless and adjusted for trading costs. To this end, I look into various trading strategies to ensure that the strategy is truly risk-free and that all costs are identified. I examine Libor swaps (fixed-for-floating interest rate swaps), corporate bonds and government bonds and refer to deviations between the synthetic and direct interest rate as the basis, i.e. the Libor basis, the government bond basis and the corporate bond basis. My results suggest that CIP arbitrage is difficult to reap and that common measures of CIP rely on trading strategies subject to rollover risk and credit risk, or fail to fully account for the trading cost.

As a point of departure, Figure 4.1 depicts the 5-year EUR/USD basis for Libor swaps, high quality corporate bonds and risk-free government bonds in two tranquil periods before and after the global financial crisis. Prior to the crisis (2004-2006), the corporate bond basis and the Libor basis were close to zero. In the same period, the government bond basis hovered between -30 and -40 basis points. Seen from the perspective of an U.S. investor, this means that U.S. Treasuries yield less than investing in German government bonds after fully covering the exchange rate risk. After the crisis (2015-2017), the Libor basis has moved into negative territory. In contrast, the corporate bond basis is fairly close to zero in both periods.

Figure 4.1 raises several questions. Why has the Libor basis widened substantially after the

[1] See for instance Du et al. (2019), Liao (2020), Sushko et al. (2016), Avdjiev et al. (2019)

[2] The Basel III framework introduces new capital and liquidity standards. This includes higher capital requirements for banks, a strengthening of banks liquidity coverage (Liquidity Coverage Ratio - LCR) and a more stable funding structure (Net Stable Funding Ratio - NSFR). Moreover, some jurisdictions have introduced Leverage Ratios limiting the amount of bank leverage independent of the risk profile of the asset side of the bank. These regulations have been gradually implemented since the global financial crisis.

[3] Long-dated is defined in this paper as 1 year to maturity and beyond.

financial crisis? The government bond basis traded well below zero already prior to the post-crisis tightening of banking regulations - what prevented market participants from exploiting cross currency deviations in presumably risk-free securities? Moreover, a wide range of bond market participants are not subject to banking regulations. Why would a relatively unconstrained hedge fund leave risk-free profit on the table if the deviations can easily be taken advantage of? These questions call for further analysis of the impediments to cross currency arbitrage in long-dated securities.

To answer these questions I first turn to the Libor basis - the difference between the direct and the synthetic Libor swap rate.[4] The Libor basis is a frequently applied measure of long-dated CIP deviations and has traded at unprecedented levels ever since the global financial crisis.[5] However, the Libor basis is not suited to measure CIP deviations due to substantial roll-over risk and the failure of the Libor swap rates to accurately reflect the costs of avoiding this roll-over risk - which I refer to as the term funding liquidity premium. The Libor swap is a derivative reflecting the expected path of the underlying short-term floating rate. Hence, to take advantage of the 5-year Libor basis, for instance, the investor has to raise funding every quarter exactly at the 3-month Libor rate over the next 5 years.[6]

Although the roll-over risk is always inherent in the Libor basis trade, it only shows up in the Libor basis if the costs of avoiding roll-over risk differ across currencies. Indeed, the Libor basis is basically a necessary compensation for such differences as the Libor swap rate in the two currencies does not reflect the true cost for borrowing and lending at the respective tenor. My empirical results suggest that cross-currency differences in the relative costs of locking in funding over longer periods - the term funding liquidity premium - is an important driver of the Libor basis after the global financial crisis. Divergence in the timing, scale and composition of central bank asset purchases contribute to the differences in the term funding liquidity premium. Furthermore, trading the Libor basis exposes the trader to credit risk in the investment leg. The considerations above substantiate that the Libor basis is not an adequate measure of CIP deviations.

To avoid the roll-over risk in Libor swaps, one may turn to corporate bonds where the principal is exchanged at the same tenor as the FX forward agreement. Hence, corporate bond rates should embed the full term funding liquidity premium at the relevant tenor and the corporate bond basis is expected to be significantly closer to zero than the Libor basis. To verify this, I construct the deviations between the synthetic and direct corporate bond rate for similar bonds. I find that the corporate bond basis is substantially closer to zero and less persistent than the corresponding deviations based on Libor swap rates. Moreover, empirical tests indicate that the long run relationship

[4]The Libor swap rate is often referred to as Interest Rate Swaps (IRS). The Libor basis is equivalent to a Cross Currency Basis Swaps (CCBS) which is quoted directly on data vendors like Bloomberg and Thomson Reuters.

[5]Several studies have shown the tight correspondence between the Libor basis and CCBS, see for instance Du et al. (2019).

[6]The underlying short-term rate in Libor swaps are typically 3-month or 6-month Libor. In this paper I use 3-month Libor rates. In currencies where Libor is not quoted, an equivalent interbank benchmark rate acts as the underlying floating rate. Although Libor is quoted in EUR, the market convention is Euribor.

between corporate bond spreads and the Libor basis is in line with the CIP-condition. These results are consistent with the hypothesis that corporate bond rates indeed account for differences in the term funding liquidity premium across currencies.[7]

Corporate bonds are typically not risk-free. Hence, the corporate bond basis can be exploited by bond issuers, but deviations do not represent round-trip arbitrage opportunities.[8] To eliminate the credit risk embedded in the corporate bond basis, a risk-free option is government bonds. Du et al. (2019) suggest that deviations between the synthetic and direct risk-free bond rate - e.g. the government bond basis - can be arbitraged by going short the "expensive" bond denominated in one currency and investing in the "cheap" bond denominated in another currency with the exchange rate risk fully covered (the short/long strategy).[9][10] The authors argue that the persistent deviations between the synthetic and direct risk-free bond rate - in their case bonds issued by the German government sponsored bank KfW - are due to stricter banking regulations introduced in the aftermath of the financial crisis.

The short/long strategy incurs substantial shorting costs in the form of haircuts and lending fees. My estimations of the shorting costs suggest that the post-crisis CIP deviations for government bonds are generally below the costs of employing the short/long strategy. The main costs in the short/long trade are haircuts and lending fees.[11] To obtain the security to sell short, the arbitrageur has to pledge collateral with the lender of the security. In the CIP trade, the value of the foreign denominated bond (long position) is not sufficient when the security lender requires a haircut. Typically, security lenders require a 5 per cent haircut when the collateral is denominated in foreign currency due to the substantial currency risk such collateral pose to the securities lender, see for instance Grohowski (2014), Duffie et al. (2002), Bassler and Oliver (2015) and Brunnermeier and Pedersen (2009). On the top of the cost of haircut the arbitrageur faces a lending fee of at least 15 basis points (Baklanova et al. (2016)).[12]

Moreover, as shown in figure 4.1, the government bond basis persistently traded below zero prior to the introduction of new banking regulations. This simple observation, also carefully documented in Du et al. (2018), substantiates that shorting costs is a more plausible explanation for the observed deviations in risk-free bonds than stricter banking regulations. It also explains why market participants not subject to banking regulations, like hedge funds, are not able to close the government

[7] These results are also consistent with the findings in Liao (2020). However, this paper conducts a more granular comparison of corporate bond rates across currencies for instance by comparing bonds issued by financial corporations domiciled in the same country.

[8] This is because, conditional on default, the payoff from the claim in the two currencies differs.

[9] Du et al. (2019) employ bonds issued by the government owned bank KfW. This means that they can compare bonds issued by the same issuer across currencies. However, as long as the bonds are risk-free it does not matter if the issuer is different. Hence, I examine the government bond basis as government bonds are traded in much deeper markets (better market liquidity), with large outstanding volume and are easier to obtain in the securities lending market - a precondition for the short/long strategy.

[10] Note that it is not possible to employ the short/long strategy to take advantage of the Libor basis as Libor swaps are derivatives with no exchange of the principal.

[11] Note that haircut applies to all types of bonds, not only government bonds.

[12] Given that these 15 basis points are based on collateral denominated in the same currency as the borrowed security it is likely a conservative estimate when the collateral is denominated in foreign currency.

bond basis.

Despite not representing round-trip arbitrage, investors with a portfolio of US government bonds can indeed enhance their return by selling U.S. government bonds and buying foreign government bonds with the foreign exchange rate risk fully covered when the basis is negative. Textbook representations of CIP suggest that with such return-enhancing opportunities available, investors will push the government bond basis towards zero by reallocating their portfolios. However, such return-enhancing opportunities were equally large prior to the introduction of new banking regulation. Hence, a more plausible explanation is a USD specific premium: investors value USD liquidity highly due to its status as the main settlement, funding and investment currency in the world. U.S. government bonds can easily be turned into USD cash (via the repo market for instance), while the costs of turning foreign denominated bonds into USD cash is much more difficult and costly - in particular in distressed markets when the demand for USD is high. This argument is in line with U.S. Treasuries being subject to a convenience yield. Note that the convenience yield hypothesis cannot explain why market participants are not employing the short/long strategy, but serves as an explanation for real money investors preference for U.S. Treasuries.

Finally, I test for round-trip arbitrage opportunities in international bond markets based on actual unsecured funding costs for high quality financial corporations in the funding leg and the risk-free government bond rate in the investment leg. This strategy captures the funding costs of potential arbitrageurs of high credit quality.[13] The trading strategy I propose assumes that one can borrow unsecured in USD and invest in a risk-free asset in one of the foreign currencies (EUR, GBP or JPY), or borrow unsecured in foreign currencies and invest in a risk-free asset in USD. I find no evidence of persistent risk-free profit opportunities in major bond markets based on this measure.

Overall, my analysis lend little support to the hypothesis that stricter banking regulation has distorted long-dated fixed income and currency markets. Although the cross currency basis is sizeable for risk-free bonds, this was also the case prior to the post-crisis tightening in banking regulations. Moreover, round-trip arbitrage in risk-free bonds is difficult to reap due to substantial costs associated with shorting bonds or due to the direct funding costs that apply when financing the trade. Real-money investors that can increase portfolio returns without adding credit risk by reallocating out of US government bonds seem to prefer securities that can easily be turned into USD liquidity. Holding liquid assets in USD is particularly valuable during a crisis and consequently act as an insurance against market volatility.

The rest of this paper is organized as follows. Section 2 provides an overview of related literature, Section 3 defines relevant concepts, Section 4 examines the Libor basis, Section 5 takes a closer look at the relation between the Libor basis and the corporate bond basis, while Section 6 discusses costs and risks associated with taking advantage of cross currency deviations between risk-free government bonds. In Section 7 I assess arbitrage opportunities in bonds after accounting for actual funding

[13]This strategy is in line with the one Rime et al. (2019b) examine for short-term maturities and can be interpreted as a way to incorporate the practice of Funding Value Adjustment (FVA).

costs. Section 8 concludes.

4.2 Related literature

This paper is closely related to a growing body of literature investigating deviations from Covered Interest Parity in long-dated fixed income markets, in particular Du et al. (2019) and Liao (2020). Du et al. (2019) suggest a short/long strategy to take advantage of deviations between the synthetic and direct bond spreads in risk-free bonds. The authors show large and persistent deviations between the direct and synthetic USD rate for bonds issued by the German government sponsored bank KfW. They argue that these deviations represent potential arbitrage opportunities and ascribe its existence to the introduction of new banking regulation. My results indicate that the long/short strategy is more costly than assumed by Du et al. (2019) due to haircut in the securities lending market. Liao (2020) looks at corporate bond spreads and establishes that the spreads are different across currencies and co-move with the Libor basis. This is consistent with my findings for the corporate bond basis. Liao (2020) links the differences in bond spreads across currencies and the Libor basis to limits of arbitrage in the two market segments and highlights regulatory constraints as a reason for the lack of arbitrage activity.

Sushko et al. (2016) investigate the Libor basis and relates the widening of the basis to hedging demand caused by currency mismatch between assets and liabilities on banks' balance sheets. The authors argue that the persistent non-zero Libor basis is due to new regulatory costs for banks limiting the arbitrage flows. Avdjiev et al. (2019) also look at the long-term Libor basis and relate the widening to the USD exchange rate. They argue that the cross currency basis widens when the USD strengthens.

Although my paper examines CIP-deviations at longer maturities, it is also closely related to a large literature on the validity of CIP in money markets. The first wave of literature on short-term CIP-deviations emerged shortly after the outburst of the global financial crisis, see e.g. Baba et al. (2008), Baba and Packer (2009a), Baba and Packer (2009b), Coffey et al. (2009), Gârleanu and Pedersen (2011), Goldberg et al. (2011), Griffoli and Ranaldo (2010) and McGuire and von Peter (2012). Common for these studies is the focus on market frictions arising as a result of the financial crisis.

As market conditions stabilized from 2014 another wave of interest in the CIP-condition and the seemingly large violations of CIP emerged, i.e. Du et al. (2019), Rime et al. (2019b), Cenedese et al. (2019), Iida et al. (2016), Wong et al. (2016) and Pinnington and Shamloo (2016). Du et al. (2019) look at the deviations in repo rates arguing that regulatory constraints are the main reason for these deviations. In contrast, Rime et al. (2019b) focus on differences in funding liquidity and unconventional monetary policy. The authors show that a narrow group of global banks face arbitrage opportunities, but that the scalability of this arbitrage is limited due to funding constraints. Cenedese et al. (2019) argue that dealers with higher leverage ratio charge less attractive FX forward prices to their customers.

Finally, my paper is also related to research on the effect of central bank balance sheet policies on bond prices and the funding liquidity premium. Specifically, it adds to an emerging literature on the balance sheet composition of private banks caused by central bank operations. For instance, Christensen and Krogstrup (2016) explain how an increase in the central bank balance sheet increases private banks' deposit ratio, while Haldane et al. (2016) and Butt et al. (2014) discuss the bank credit channel of central bank balance sheet policies. Moreover, Abidi and Miquel-Flores (2018) find that corporate bonds eligible under the ECB's corporate asset purchase program experienced a significant yield reduction compared with those not eligible. In this paper I relate central bank balance sheet policies to funding liquidity through higher demand for bonds and an improvement in the deposit base for banks.

4.3 Covered Interest Parity

This section clarifies the main concepts in the paper - Covered Interest Parity, the cross currency basis and the requirements for arbitrage.

Covered Interest Parity (CIP) Generally, CIP can be expressed by the following equation:[14]

$$\left(1 + r_{m;\$}\right) = \frac{F_m}{S}\left(1 + r_{m;\star}\right), \tag{4.1}$$

that is, the direct interest rate ($r_{m;\$}$) equals the synthetic FX swap implied rate $\frac{F_m}{S}\left(1 + r_{m;\star}\right)$, where F_m is the forward exchange rate, m is the maturity and S is the spot exchange rate. The subscript t for time is suppressed for simplicity.

Equation 4.1 holds if the forward and the spot rate (the hedging cost) is equal to the interest rate differential. By applying log approximation equation 4.1 can be written as:

$$f_m - s \approx r_{m;\$} - r_{m;\star} \tag{4.2}$$

At a given tenor m, the FX hedging component, i.e. $f_m - s$, is homogenously priced in the interdealer market and can easily be obtained through data vendors like Bloomberg and Thomson Reuters.[15] In contrast, one can compute a plethora of interest rate differentials ($r_{m;\$} - r_{m;\star}$) by using the interest rates on various fixed income securities. Consequently, two important questions arise. First, which interest rate differential corresponds to the hedging cost (interest rate differential) in the foreign exchange market? Second, which instruments can be used to construct proper

[14] Subscript t for time is dropped for simplicity.

[15] Interdealer transactions as quoted on Bloomberg and Thomson Reuters are typically subject to two-way variation margins leading to low degree of price dispersion.

arbitrage strategies? The answers to these questions are crucial when analyzing deviations from CIP. Since a cross currency trade necessarily involves the exchange of currencies, the interest rate differential priced in the FX swap market must correspond to an interest rate differential composed by instruments where funding can be raised and money can be invested at the relevant tenor.

The cross currency basis In line with the recent literature on CIP, I refer to the deviation from the general CIP-equation (equation 4.1) as the cross currency basis. Hence, the cross currency basis (ρ_m) is defined as follows:

$$\rho_m = \left(1 + r_{m;\$}\right) - \frac{F_m}{S}\left(1 + r_{m;\star}\right) \tag{4.3}$$

I examine three cross currency bases based on the following fixed income instruments; Libor swaps (interest rate swaps), corporate bonds and government bonds. I refer to the three bases as the Libor basis, the corporate bond basis and the government bond basis, respectively. It is important to stress that each basis potentially can be traded with profit when it deviates from zero, but this does not necessarily imply viable *arbitrage* opportunities.

Covered Interest Rate Arbitrage The requirements for an implementable round-trip arbitrage trade imply that i) the trade is adequately adjusted for the transaction costs; (ii) the instruments involved need to be tradeable; and (iii) the sequence of trades involved is free of risk for the arbitrageur.

Taking bid/ask spreads into account, and both from the perspective of U.S. and foreign borrowing, the CIP-trade is *not* profitable under the following conditions:

$$\left(1 + r^a_{m;\$}\right) \geqslant \frac{F^b_m}{S^a}\left(1 + r^b_{m;\star}\right) \tag{4.4}$$

$$\left(1 + r^a_{m;\star}\right) \geqslant \frac{S^b}{F^a_m}\left(1 + r^b_{m;\$}\right) \tag{4.5}$$

where the superscripts a and b symbolize ask and bid rates, respectively, and $r^a > r^b$. Equation (4) implies that the funding rate (ask) in USD has to be equal to or higher than the synthetic investment rate (bid) measured in USD for the no-arbitrage condition to hold. Similarly, Equation (5) implies that the funding rate (ask) in the foreign currency has to be equal to or higher than the synthetic investment rate (bid) measured in foreign currency for the no-arbitrage condition to hold.[16]

As I will discuss later, the bid/ask spreads constitute a small part of the trading costs in the CIP trade. The largest part is associated to the costs of obtaining the necessary funding at the relevant maturity and potential short-selling costs. It is also important that the security in the investment leg is risk-free.

[16] Note that the currency convention, i.e. if it is EUR/USD or USD/EUR, matters for the exact specification of the equations. Equation (4) and (5) are based on USD as the base currency.

4.4 The Libor basis

This section examines a frequently reported measure of long-dated CIP deviations - the Libor basis.[17] The Libor basis (ρ_m^{Lib}) is the difference between the direct and the synthetic Libor swap rate:

$$\rho_m^{Lib} = \left(1 + c_{m;\$}\right) - \frac{F_m}{S}\left(1 + c_{m;\star}\right), \tag{4.6}$$

where $c_{m;\$}$ is the USD Libor swap rate, $c_{m;\star}$ is the foreign currency Libor swap rate, while F_m and S are the forward exchange rate and the spot exchange rate, respectively. Subscript m refers to the maturity. Figure 4.2 depicts the evolution in the 5-year Libor basis for EUR, GBP and JPY, against USD. The Libor basis traded fairly close to zero across all three currency pairs prior to 2008. Since the onset of the global financial crisis, the Libor basis has been volatile and persistently below zero across the currency pairs.

At first glance it may seem like the post-crisis widening of the Libor basis convincingly represents large and persistent deviations from CIP and consequently opportunities to reap arbitrage profit. However, the properties of the underlying Libor swap rates in the Libor basis challenge this interpretation. If the 5-year Libor basis is minus 35 basis points between EUR and USD, a number close to the post-crisis average for the 5-year EUR/USD Libor basis, it means that the 5-year Libor swap rate in USD is 35 basis point lower than the comparable alternative in EUR after the EUR/USD exchange rate risk is fully covered. Theoretically, one would expect market participants to pay the Libor swap rate in USD, receive the Libor swap rate in EUR and hedge the FX risk in order to take advantage of the basis. The problem is that the Libor swap is *not* a security where cash can be raised or placed at the 5-year tenor.

Given a negative Libor basis of 35 basis points, market participants that are able to borrow funds exactly at 3-month Libor in USD and invest exactly at 3-month Libor in EUR on a rolling basis over the next five years and simultaneously exchange currencies and hedge the foreign exchange rate risk for 5 years will earn an annual profit of 35 basis points. However, a non-zero Libor basis should not be interpreted as an arbitrage opportunity as taking advantage of the basis implies both rollover risk in the funding leg and credit risk in the investment leg. Hence, there is no reason to expect the Libor basis to be zero at all times. Even though a non-zero Libor basis does not indicate arbitrage, the post-crisis evolution in the Libor basis has been unprecedented. The next subsection examines potential drivers of the Libor basis.

The main reason for the inadequacy of the Libor basis as a measure of CIP-deviations stems from the fact that the Libor swap rate is a derivative connected to a short-term interest rate and not a cash instrument. In a Libor swap the counterparts exchange a fixed coupon rate for a variable

[17] The focus in this analysis is on maturities ranging from 2 to 10 years. The Libor basis is effectively quoted in the market as the cross currency basis swaps. Several papers have shown the correspondence between the Libor basis calculated as the Libor swap rate plus the FX implied interest rate differential and the cross currency basis swap, see for example Du et al. (2019). In order to stick to a fixed terminology, I consistently refer to the "Libor basis".

coupon rate equal to the 3-month Libor rate over the term of the swap.[18] At initiation, the value of the Libor swap is zero. The Libor swap rate is therefore the yield to maturity the market is willing to pay in order to receive a path of unknown 3-month Libor interest rate payments throughout the term of the Libor swap contract. To take advantage of a negative Libor basis the trader needs to obtain funding in USD and invest the proceeds in EUR since the participants in the foreign exchange market require that USD is exchanged and delivered against EUR. However, as the Libor basis is based on Libor swaps - a derivative with no exchange of the principal - it is not straight forward to borrow or invest at the interest rates used to compute the Libor basis.

To obtain the necessary funding to exploit a negative Libor basis, market participants have to roll over 3-month Libor borrowing in USD throughout the term of the Libor swap (in this example 5-year). The Libor swap rate in USD can then be locked in by paying the fixed rate and receiving the 3-month U.S. Libor throughout the lifetime of the Libor swap contract. The interest rate payments (equal to the 3-month U.S. Libor rate) on the funding will be canceled out by the incoming 3-month U.S. Libor rate from the Libor swap and the trader is left paying the fixed Libor swap rate in USD. On the investment side, the Libor basis assumes an unsecured investment in a representative Libor panel bank in the investment currency, for instance EUR. The trader then rolls over the unsecured deposit at 3-month EUR Libor (or an equivalent rate like Euribor), pays the 3-month EUR Libor in the Libor swap and receives the Libor swap rate in EUR. The trader is then left with the EUR Libor swap rate on its investment.

4.4.1 Determinants of the Libor basis

The rollover risk in the Libor swap serves as a natural starting point when searching for potential drivers of the Libor basis. The Libor swap rate represents the expected average of 3-month Libor over the term of the Libor swap, but not the actual term funding cost at longer tenors. This implies that cross currency differences in the term funding liquidity premium not embedded in the Libor swap rates may influence the Libor basis. To see this, imagine a trader who wants to take advantage of the Libor basis. Since there is no exchange of the principal, only interest rate payments in a Libor swap the trader of the Libor basis has to raise funding every third month while the cash proceeds are exchanged and locked in another currency for a long period of time. Moreover, the trader place the funds in the new currency at 3-month Libor. The trader has now basically traded one currency for another at a long tenor, while paying and receiving the expected path of short term rates in the respective currencies. If the compensation for locking in funds for a long term - the term funding liquidity premium - in the currency the trader gave up is higher than in the currency she receive, a similar compensation must be given in the FX forward market. Such compensation shows up as a Libor basis.

[18] In some currencies the underlying interest rate in the swap is the 6-month rate. In main currencies swap rates with both 3-month and 6-month rates as underlying are quoted. The Libor basis that corresponds to cross currency swaps is based on 3-month Libor swap rates.

To test this hypothesis, I resort to the relative size of the central bank balance sheets as a proxy for differences in the term funding liquidity across currencies. This implicitly assumes that central bank balance sheet policies have an effect on the term funding liquidity premium.

To justify this assumption, I start with the stylized fact that the central bank has the power to influence the short-term funding liquidity premium in its own currency due to its control over the supply of the most liquid asset in the economy - central bank reserves. It is already well established that standard central bank operations affect the funding liquidity premium at short horizons, see for instance Hamilton (1997) and Carpenter and Demiralp (2008). Furthermore, in their seminal paper, Kashyap and Stein (2000) establish that even relatively small asset purchases by the Federal Reserve - conducted as part of the regular implementation of monetary policy prior to the financial crisis - affect banks' liability composition through relative changes in the deposit base. Such changes in the liability composition consequently affects lending. One important lesson from Kashyap and Stein (2000), further supported in Drechsler et al. (2017), is that deposits is a special source of funding for banks which may not be easily replaced by market funding and that many types of deposits, independent of the maturity, can be regarded as long-term funding for banks.

Large-scale asset purchases may have a similar effect on the long-term funding liquidity premium as standard central bank operations have on the short-term funding liquidity premium. One potential channel is through an increase in non-bank deposits. For instance, when the central bank purchases assets held by the non-bank sector, the central bank prints money to finance its purchases and thereby induces an increase in non-bank deposits at commercial banks. The new non-bank deposits show up on the liability side on commercial banks' balance sheets and are matched by highly liquid central bank reserves on banks' asset side. Additional deposits and a higher level of central bank reserves improve banks' funding and liquidity position[19]

Indeed, deposits relative to non-cash assets have increased significantly after the introduction of large-scale asset purchases in the US, UK, Japan and the euro area.[20] Normally, non-cash assets and deposits grow at a fairly similar pace. However, in the aftermath of central bank asset purchases the deposit growth has outpaced the non-cash asset growth.[21] Higher growth in deposits than in non-cash assets may lead to lower demand for long-term market funding (bond issuances) and improved term funding liquidity for banks as banks' less liquid assets can increasingly be financed by deposits.

Hence, large-scale asset purchases may reduce the term funding liquidity premium for banks in the respective currency through the deposit channel. In turn, this affects the relative term funding liquidity premium across currencies for all market participants and it becomes relatively cheaper to obtain long-term funding in the respective currency. However, because the Libor swap rate does not embed the term funding liquidity premium, the interest rate differential based on Libor

[19]There may also be other channels like the direct price impact of central bank purchases of corporate bonds, see for instance Abidi and Miquel-Flores (2018).

[20]This can be seen in figure 4.B.2 in Appendix B.

[21]See Appendix B and Christensen and Krogstrup (2016) for a detailed discussion of how asset purchases may affect the deposit base.

swap rates does not change while the hedging cost adjusts to the fact that the relative price of the currencies changes (because the notional in the two currencies changes hands when exchanging from one currency to another). Consequently, the Libor basis widens.

The Libor basis may also be effected by discrepancies between the underlying Libor benchmark rates across currencies. The Libor swap rate inherits the characteristics of the underlying 3-month Libor benchmark rate. Differences across benchmark rates, e.g. the panel composition, transmit to the Libor basis through the Libor swap rates in the two currencies. If the Libor swap rates are not comparable due to differences in the underlying instrument, a compensation is needed. Such a compensation shows up as a Libor basis.

Libor benchmark rates have been under scrutiny, evidently manipulated and subject to various reforms over the past 10 years. Since Libor is based on quotes rather than actual transactions, these rates are sensitive to the panel banks' own assessment. The various reforms and the touch of banks' own judgement may cause differences in the benchmark rates across currencies. I proxy such cross currency discrepancies by the spread between 3-month Libor rates and actual funding costs for similar issuers in the commercial paper market. In cases where the spread between the benchmark rate and actual funding costs for banks with a specific rating differs across currencies, this is a sign that the benchmark rates contain different information, for instance in terms of methodology or credit quality of the panel banks.[22] I use these cross currency differences as a proxy for benchmark rate discrepancies.[23]

Empirical strategy I examine the Libor basis and the potential determinants laid out above by employing a panel regression on three currency pairs - EUR/USD, GBP/USD and JPY/USD.[24] I investigate the Libor basis for 2, 5 and 10 years maturity and my sample runs from 2010 to 2017 with weekly frequency due to data availability for the central bank balance sheets. The regression is specified as follows:

$$\begin{aligned}\Delta LB_{i,t}^{m} = \beta_0 + \beta_1 \Delta LB_{i,t-1}^{m} + \beta_2 \Delta(Bal_{i,t}/Bal_{fed,t}) + \beta_3 \Delta CDSsprFR_t \\ + \beta_4 \Delta(LIBCPspr_{i,t} - LIBCPspr_{US,t}) + \beta_5 LB_{i,t-1}^{m} + \epsilon_{i,t} \quad (4.7)\end{aligned}$$

where Δ is the first difference operator, $LB_{i,t}^{m}$ is the Libor basis for currency i (against USD)

[22] Figure OA.1 in the online appendix illustrates the relevant 3-month Libor rates and the non-bank funding cost measured by the 3-month commercial paper rate (CP rate) for high quality banks (A1/P1 short-term rating) differ across currencies.

[23] Libor and other Ibor panel banks have generally A1/P1 rating. After the financial crisis, some panel banks have been downgraded. However, the effect of lower rated banks in the Libor fixing should be minimal as the methodology ensures that outliers are removed, e.g. the four lowest and highest contributions. See the online appendix for further details about benchmark rates.

[24] Table OA.I in the online appendix shows the results from a seemingly unrelated regression (SUR), an alternative to the panel regression allowing currency specific coefficients. By employing a SUR model, potential correlation between the residuals across currencies is taken into account.

at time t with maturity m, $Bal_{i,t}$ is the indexed balance sheet for currency i, $Bal_{fed,t}$ is Federal Reserve's indexed balance sheet, $CDSsprFR_t$ is the difference between the 5-year French CDS price denominated in USD and EUR added as a control variable in order to account for the impact of the European sovereign debt crisis and the euro break-up risk.[25] The Euro crisis increased the political risk of holding euro assets in addition to a general surge in market uncertainty. The sovereign debt crisis in the euro area can be characterized as a period with severe turmoil across financial markets and large heterogeneity in banks' funding costs depending on the country of incorporation and the asset composition of the bank. Finally, $LIBCPspr_{i,t}$ is the spread between 3-month Libor and commercial paper rate in currency i and $LIBCPspr_{US,t}$ is the corresponding spread in USD.

The model is specified on first differences, solely focussing on short-run effects, because of non-stationarity of some variables on levels. Standard unit-root tests indicate that all variables are stationary after differencing. Johansen cointegration tests show mixed results across currencies and lack of cointegration between the main variables. The lagged dependent variable on first differences is included to shed light on the persistence of the effects. A positive coefficient estimate on this variable would suggest that the price adjustment in the previous period is not reversed.

Finally, the lagged dependent variable on levels act as an "error correction" term as the Libor basis is potentially a stationary variable. Note that the focus on short-run effects means that the change in the relative central bank balance sheet has to be interpreted as a flow rather than a stock effect.

Regression results Table 4.1 depicts the results from the panel regression specified in equation 4.7 for three different maturities - 2, 5 and 10 years. The results indicate that the relative central bank balance sheet affects the Libor basis. An increase in the non-US central bank balance sheet relative to the Federal Reserves balance sheet (β_2) is associated with a decline in the Libor basis, consistent with asset purchases improving the funding liquidity and consequently affect the Libor basis. Specifically, a one standard deviation change in the relative central bank balance sheet (β_2) is followed by a 0.15 basis point change in the 5-year Libor basis.

As expected, the results also suggest that a higher spread between the French CDS price denominated in USD and Euro (β_3) leads to a more negative Libor basis, i.e. an increase in the break-up risk is associated with a higher cost of synthetic USD funding. Specifically, during the height of the sovereign debt crisis in Europe USD investors worried about the health of some banks balance sheets - especially those exposed to European sovereign debt - and many globally active banks were forced to obtain USD through the FX swap market. This put a downward price pressure on the Libor basis.

Finally, a higher Libor-CP spread in non-US currencies compared to the US Libor-CP spread (β_4) leads to a lower Libor basis. The relative Libor-CP spread between non-US currencies and

[25] I use French government CDS prices due to data quality. German CDS prices show the same pattern, but suffer from more frequent data gaps.

the US dollar measures the contemporaneous discrepancies in the benchmark rates relative to the actual non-bank funding rate across currencies. These discrepancies are compensated by a widening of the Libor basis. Interestingly, the regression coefficients across the term structure indicates a declining importance of the benchmark rate discrepancies. A one basis point increase in the non-US Libor-CP spread versus the US leads to a 0.12 basis point decline in the 2-year Libor basis. The corresponding decline in the 10-year Libor basis has been 0.073 basis points. The striking pattern observed in the benchmark rate coefficients is consistent with market participants interpreting a share of the benchmark rate discrepancies as transitory (declining effect along the term structure). For example, the strains in US money markets due to the European sovereign debt crisis may have been considered to be transitory and benchmark rates in different currencies may react differently to the underlying market stress. If this effect was perceived to be a short lived the coefficients should indeed be smaller than one and declining along the term structure since the transmission from the 3-month Libor to the longer term Libor swap rates and further to the Libor basis depends on the expected persistence of the discrepancies between the 3-month Libor rates.

4.5 The corporate bond basis

The discussion above suggests that the Libor basis is not an accurate measure of CIP deviations because Libor swap rates do not adequately capture the full funding costs across currencies. To avoid this problem I turn to the corporate bond basis by obtaining granular corporate bond data from Barclays/Bloomberg running from 2010 to the end of 2017.[26] This allows the calculation of zero coupon corporate bond spreads based on country of incorporation, rating of the bond, issuance currency and maturity.[27] I compute the corporate bond basis (ρ_m^{Corp}) for issuers with similar characteristics as follows:

$$\rho_m^{Corp} = \left(1 + y_{m;\$}\right) - \frac{F_m}{S}\left(1 + y_{m;\star}\right), \tag{4.8}$$

where $y_{m;\$}$ is the direct zero-coupon corporate bond rate denominated in USD, $y_{m;\star}$ is the zero-coupon corporate bond rate in foreign currency and $\frac{F_m}{S}$ is the hedging cost. That is, $\frac{F_m}{S}\left(1 + y_{m;\star}\right)$ is the synthetic zero-coupon corporate bond rate based on foreign currency at maturity m.[28]

As a starting point, it is useful to look at the relation between the corporate bond basis and the

[26] It is important to note that the corporate bond market is highly fragmented. In my analysis of the corporate bond basis the Barclays/Bloomberg data are restricted to bonds with the minimum outstanding volume of around 200 million USD. After the financial crisis both market liquidity and funding liquidity have been gained importance and the price differences between bonds with different outstanding volume but otherwise similar/equal may be substantial. Moreover, among more standard features of the bond as rating and remaining maturity, I condition on the country of incorporation of the bond issuer.

[27] More details regarding the data and the calculation of bond spreads can be found in Appendix A.

[28] Subscript t for time is dropped for simplicity. Mid prices from the foreign exchange market are applied to simplify the illustration as deviations between the synthetic and direct corporate bond rate do not represent arbitrage opportunities due to the credit risk in corporate bonds. Table OA.VI in the online appendix illustrates the bid/ask spreads in the FX hedging market and shows these spreads would only account for a couple of basis points.

Libor basis. Corporate bond rates are typically compared to the Libor swap rate (interest rate swap) as a measure for the bond spread.[29] In contrast to Libor swaps, corporate bonds are cash instruments where the principal is exchanged over the full maturity of the bond. Corporate bond rates should therefore embed the term funding liquidity premium. Hence, the corporate bond spread is expected to be positive. However, there is nothing that prevents bond spreads for the similar corporations to differ across currencies. For instance, in the presence of differences in the term funding liquidity premium, the spread between the corporate bond rate and the Libor swap rate (the corporate bond spread) should also differ across currencies. If the Libor basis exactly compensates for potential differences in corporate bond spreads the corporate bond basis is zero.

To show the relationship between bond spreads and the Libor basis I decompose the zero coupon corporate bond rate, y, into the zero coupon Libor swap rate, c, and the corporate bond spread, b:

$$y_m = c_m + b_m, \tag{4.9}$$

Hence, the bond spread, b_m, is the difference between the corporate bond rate, y_m, and the Libor swap rate, c_m, at maturity m. For a given issuer, differences in the term funding liquidity premium show up in differences in corporate bond spreads across currencies. By combining equation 4.8 and 4.9, the corporate bond basis (in logs) can be expressed as a function of corporate bond spreads and Libor swap rates:

$$\rho_m^{Corp} \approx c_{m;\$} + b_{t;\$} - (f_m - s) - c_{m;\star} - b_{m;\star} \tag{4.10}$$

A zero corporate bond basis implies that the difference between the corporate bond spreads equals the Libor basis. Equation 4.10 illustrates that the corporate bond basis is basically the Libor basis plus the cross currency bond spread differential. After isolating the bond spreads, the remaining elements constitute the Libor basis (i.e. the log version of equation 4.6):

$$\rho_m^{Corp} \approx \rho_m^{Lib} + (b_{m;\$} - b_{m;\star}) \tag{4.11}$$

Figure 4.3 illustrates the empirical relationship between the bond spread differential, the Libor basis and the corporate bond basis. As expected, and consistent with the term funding liquidity premium hypothesis, corporate bond spreads differ substantially across currencies. The left hand side of the panel, graph a and c, depicts the corporate bond spreads for high quality financial corporations in EUR and USD, and JPY and USD, respectively. Moreover, the difference between the bond spreads corresponds closely to the Libor basis as shown in graph b and d in figure 4.3. This means that the corporate bond basis is relatively close to zero. The exception is during the European sovereign debt crisis, a period characterized by high political risk and generally high degree

[29] Bond spreads are commonly referred to as credit spreads or z-spreads. However, since a main point in this analysis is that bond spreads across currencies may vary due to differences in the term funding liquidity premium, the terminology bond spreads is used in this paper.

of uncertainty in financial markets, highlighted by the grey shaded area in the graphs.

Overall, the data suggest that the discrepancies in the funding liquidity premium are embedded in corporate bond prices. This observation supports the hypothesis that the Libor basis expresses cross currency differences in the term funding liquidity premia that are not reflected in Libor swap rates.[30] The co-movement between the Libor basis and the corporate bond spread differential sheds light on the development in bond markets. The differences in corporate bond spreads for similar issuers mean that the funding liquidity premium in bonds varies across currencies as the credit risk component should be fairly similar. The widening of the Libor swap basis is necessary to equalize the synthetic and direct corporate funding costs.

A natural implication of the discussion above is that bond spreads should be similar across currencies prior to the financial crisis as the Libor basis was close to zero in the pre-crisis period. Figure 4.4 shows the senior bond spreads in EUR and USD for investment grade financial issuers in two periods - 2004-2007 and 2015-2017 obtained from the Barclays/Bloomberg global financial indices for EUR and USD. The average maturity of the bonds included varies slightly and the credit quality of the included bonds can vary within the investment grade environment. Despite being a crude measure, figure 4.4 confirms that bond spreads were very close prior to the crisis. The right-hand panel depicts the difference between the bond spreads (EUR minus USD) in two periods, the first from 2004 to 2007 and the second from 2015 to 2017. Between 2004 and 2007 the difference in bond spreads never exceeded 10 basis points. In contrast, between 2015 and 2017 the difference between the bond spreads in the two currencies increased substantially. This happened in tandem with the widening of the Libor basis. It is worth noting that a zero Libor basis implies that the bond spreads across currencies have to be equal for the corporate bond basis to hold, i.e. if the Libor basis is interpreted as a measure of CIP it either implies that the central bank has no room to affect *bond spreads* in its own currency or that the ability of one central bank to affect bond spreads will be transmitted to all other currencies as well for CIP to hold in corporate bonds.

The corporate bond basis, however, does not reflect round-trip arbitrage opportunities. The reason is that the investment currency is assumed invested in a risky corporate bond. Despite high rating and relatively good credit quality, most corporations cannot be considered risk-free. However, the corporate bond basis can be exploited by globally active issuers in their search for lowest possible funding cost. This means that the corporate bond basis should be close to zero. I now examine the empirical relationship between the Libor basis and the corporate bond spread differential before turning to risk-free arbitrage strategies in section 4.6,

[30] I do not adjust for so-called quanto spreads connected to potential jump risk in the foreign exchange rate in the case of default. The existence of quanto spreads implies a room for the corporate bond basis to deviate from zero without violating CIP.

4.5.1 Empirical analysis of the corporate bond basis

This subsection examines the empirical relationship between the 5-year Libor basis and the corresponding corporate bond spread differential in EUR, JPY and GBP against USD.[31] Essentially, I look at how well corporate bond rates are aligned with CIP across currencies.[32] As explained above, the corporate bond basis is zero (no deviations from CIP) when the bond spread differential equals the Libor basis.

The main empirical concern is that corporate bond spreads and the Libor basis are potentially endogenously related as the FX swap price may influence the relative demand for bonds across currencies for given bond prices and vice versa. Hence, I employ a vector error correction framework. An advantage of this approach is that I can test for the long-run relationship between the two. The estimates also give an indication whether it is bond prices or the hedging price (the FX swap price) that adjust most towards the long run equilibrium.

I apply the following Vector Error Correction Model on daily data to shed light on the cointegrating relationship and the speed of adjustment from disequilibrium towards its equilibrium level:[33]

$$\Delta bspr_t = \beta_{11}\Delta bspr_{t-1} + \beta_{12}\Delta bspr_{t-2} + \beta_{13}\Delta LB_{t-1} + \beta_{14}\Delta LB_{t-2} + \lambda_{bspr}(bspr_{t-1} - \alpha_1 LB_{t-1}) + v_t^{bspr} \tag{4.12}$$

$$\Delta LB_t = \beta_{21}\Delta bspr_{t-1} + \beta_{22}\Delta bspr_{t-2} + \beta_{23}\Delta LB_{t-1} + \beta_{24}\Delta LB_{t-2} + \lambda_{LB}(bspr_{t-1} - \alpha_1 LB_{t-1}) + v_t^{LB} \tag{4.13}$$

where $bspr_t$ is the 5-year bond spread differential and LB_t is the 5-year Libor basis for the respective currency pair. The λ_{bspr} is the adjustment parameter for the bond spread differential while λ_{LB} is the corresponding adjustment parameter for the Libor basis. After normalizing the coefficient on $bspr_t$ to 1, the cointegrating relationship predicted by the CIP - in order to keep the synthetic corporate bond rate equal to the direct rate - implies a cointegrating vector (1,-1). This means that in the long-run $bspr_t = LB_t$. The error-correction term in each equation above is then $bspr_{t-1} = LB_{t-1}$, meaning that if $bspr$ is above its long-run equilibrium or LB is below. Hence, I expect $\lambda_{bspr} < 0$ and $\lambda_{LB} > 0$.

Table 4.2 reports the results from both an unrestricted model and a model specification where the cointegrating vector is restricted to (1,-1). The unrestricted model indicates that for EUR/USD and USD/JPY the cointegrating coefficient, α_1, is very close to -1. The adjustment coefficients

[31] I also provide the results for the 2-year and 10-year tenor in the online appendix.

[32] Note that in this section I am not looking for CIP-arbitrage (due to the credit risk in corporate bonds), but deviations from the general CIP equation.

[33] Table OA.II in the online appendix confirms a cointegrating relationship between the Libor basis and the bond spread differential.

for both currencies have the expected sign, have similar magnitude and are statistically significant at conventional significance levels. The major part of the adjustment comes through the bond spread differential (about 2.5 per cent). The adjustment coefficient on the basis swap is about 1 per cent per day. For the GBP/USD cross, α_1 is only - 0.56. Moreover, for GBP the bond spread differential seems to take all the burden of adjusting to long run equilibrium. When restricting the long run relationship to $bspr_{t-1} = LB_{t-1}$, the adjustment parameters are basically unchanged and the Likelihood Ratio test for binding restrictions indicate that this restriction is not binding for any of the currency pairs.

My results indicate that CIP for corporate bond prices issued by similar issuers cannot be rejected in the long run despite the large and persistent non-zero Libor basis. This is due to the joint movement in the bond spread differential and the cross currency Libor basis. Furthermore, the analysis shows that the adjustment from disequilibrium is relatively slow and driven by both the Libor basis and bond spreads. However, the largest part of the adjustment stems from the bond spreads as these are more volatile than the Libor basis.

4.6 The government bond basis

In this section I investigate risk-free rates. To this end, I compute the government bond basis in the same manner as the Libor and the corporate bond basis. Government bonds, at least for the currencies in this analysis, are close to risk-free and frequently traded in liquid markets. Equation 4.14 shows the computation of the government bond basis where $g_{m;\star}$ and $g_{m;\$}$ are the zero coupon government bond rates in foreign currency and USD at maturity m, respectively.

$$\rho_m^{GovBasis} = \left(1 + g_{m;\$}\right) - \frac{F_m}{S}\left(1 + g_{m;\star}\right), \tag{4.14}$$

Figure 4.5 depicts the difference between the synthetic and the direct US dollar rate based on 2, 5 and 10-year zero coupon government bonds. Negative values indicate that the synthetic bond spread is above the corresponding US Treasury rate, i.e. the USD return on foreign denominated government bonds is higher than for US government bonds after the foreign exchange rate risk is fully hedged.

The figure illustrates substantial deviations between the synthetic and the direct US treasury rate across all currency pairs since 2000. The deviations over the past five years are not *large* in a historical perspective. For instance the average 5-year JPY/USD government bond basis is minus 45 basis points in the period between 2000 and 2006, while the corresponding average is minus 50 basis points between 2014 and 2017 (a tranquil period in the aftermath of the financial crisis and the sovereign debt crisis in the Euro area). Indeed, there is no indication that the deviations can be attributed to the banking regulations implemented after the global financial crisis. Although the synthetic bond spread based on Japanese government bonds is currently above the corresponding

US Treasury rate (leading to a negative government bond basis), the deviations were even larger in the period between 2000-2003, a period where the USD/JPY Libor basis traded close to zero. The government bond basis in the two remaining currencies have varied substantially, but have more or less closed the gap towards the end of the sample.

The intention of figure 4.5 is to illustrate that the cross currency deviations in government bond markets are not a post-crisis phenomenon pointing to impediments to arbitrage beyond the post-crisis tightening of banking regulations. Hence, I turn to an examination of the potential costs of trading the cross currency CIP deviations in bonds, particularly focussing on government bonds.

4.6.1 Trading the government bond basis - costs and risks

Du et al. (2019) propose a short/long strategy to take advantage of the risk-free bond basis, i.e. to short-sell the security denominated in the currency with the highest relative price.[34] The various steps in the strategy are:

1. Borrow, say, a risk-free US security with m-year remaining maturity from a securities lender, and short-sell this security at rate $r_{m;\$}$
2. With the proceeds of the sale of the security, buy euros spot to obtain $1/S$ euros, and simultaneously enter a forward contract F_m reversing the currency exchange at a predetermined price in m years (effectively entering a FX swap contract),
3. Invest the euro funds at the currently available m-year risk-free euro rate $r_{m;\star}$.
4. Use the euro-denominated bond as collateral for the borrowed security denominated in USD.

Du et al. (2019) find substantial deviations between the synthetic and the direct interest rate on bonds issued by KfW. KfW is a German government sponsored bank and can be considered to be close to risk-free. Hence, the authors suggest persistent arbitrage opportunities in long-dated bond and currency markets. Despite that the government bonds in my analysis are not issued by the same issuer this should not matter as long as the government bonds are considered to be free of risk.[35] Indeed, government bonds are better suited for the short/long trade than for instance KfW bonds as the market liquidity is better and government bonds are more likely to be available by securities lenders. The short/long strategy involves substantial trading costs beyond the bid/ask spreads. Although Du et al. (2019) consider the lending fee in the securities lending market, other important short-selling costs apply. I discuss the costs of short-selling fixed income securities below.

[34] Short-selling means borrowing the security and subsequently sell the security to raise cash.

[35] The main risk for the security lender is the fact that the collateral is denominated in another currency which implies that the general interest rate level in the two currencies can develop differently and the exchange rate can move substantially.

Haircut and lending fees Security lenders typically require over-collateralization (haircut) as risk mitigation mechanism in the case of the default of the security borrower. Haircut is necessary even when the trade is subject to variation margin due to the price and exchange rate risk the security lender is exposed to between the last margin call and the potential liquidation of the collateral.[36] If a default occurs, it may take some time to liquidate the security and the cross currency nature of the collateral increases the risk of a loss due to changes in the price of the collateral relative to the security on loan *and* exchange rate movements between the last margin payment and the liquidation of the collateral.

Unfortunately, data on haircut are scarce. However, several pieces of information collectively provide evidence on both the level and importance of haircut in the repo and securities lending market. For instance, Baklanova et al. (2016), a pilot study conducted by the Office of Financial Research and the New York Fed on the US securities lending market, present data on the last three months of 2015. This study finds that the haircut level ranges from 2 to 5 per cent for government bonds. The average lending fee for US government bonds varied between 15 and 20 basis points during the last three months of 2015, see table 4.3. The data hide potential differences in the lending fee and haircut between USD denominated collateral and foreign currency denominated collateral. Most of the transactions in USD are collateralized by USD denominated collateral. The haircut on foreign denominated collateral is therefore likely to be in the high end of the haircut range presented in Baklanova et al. (2016) due to the exchange rate risk connected to foreign currency collateral.

The difference between domestic and foreign currency collateral is emphasized by the Investment Company Institute (ICI). Grohowski (2014) states the following: "A U.S. regulated fund must receive collateral equal to at least 100 percent of the value of the securities on loan. In practice, funds require 102 percent collateral for domestic securities and 105 percent for international securities. Because loaned securities must be available for recall on short notice, the collateral that funds can accept from borrowers must be highly liquid, such as cash, government securities, or bank letters of credit."[37] U.S. regulated funds are not the only player in the U.S. securities lending market, but constitute a large participant together with pension plans and insurance companies, see Adrian et al. (2013). The practice of requiring a 5 per cent haircut on foreign denominated collateral in securities lending transactions is also pointed out by Duffie et al. (2002) and Bassler and Oliver (2015).[38]

Furthermore, the New York Federal Reserve publishes haircut level data on repo transactions. These data are based on repo only, not on securities lending transactions. However, securities lending is a form of repo meaning that the numbers give an overall picture of the haircut levels. The median level has over the past 6 years hovered between 2 and 5 per cent.[39] Note that a borrower in the tri-party market cannot freely choose the security to be delivered. An important presumption of the

[36] Variation margin is additional collateral posted in order to reflect price movements in the underlying security on loan. The exchange rate risk applies only to transactions where the collateral is denominated in foreign currency.

[37] 102 and 105 per cent collateral are for all practical purposes equivalent to 2 and 5 per cent haircut, respectively.

[38] See also Hu et al. (2019) for a detailed analysis of haircut levels in the U.S Tri-Party repo market.

[39] See figure OA.5 in the online appendix for a time series of the data from New York Federal Reserve.

short/long trade is that a pre-specified security is delivered. In a special repo where the security lender requires a specific security, both the interest rate (lending fee) and the haircut may be less attractive from the perspective of the cross currency arbitrageur.

Finally, data from EUREX Clearing - a leading clearing house in Europe - suggest a haircut level of at least 5 per cent on foreign denominated collateral. The numbers suggest the haircut rates applied by EUREX clearing for a range of currencies against the USD. The cross currency haircut rates vary between 4 and 8 per cent.[40] Higher haircut levels for foreign currency denominated collateral is also reflected in most central banks' collateral frameworks, either by a higher haircut (Central Bank of Norway and BoE) or larger mark-down on the valuation of the collateral (ECB).

Overall, the indicative evidence above points in the same direction: consistent with the extensive literature on US repo markets haircut is an important part of the risk mitigation for the securities lender and can be substantial for trades relying on cross currency collateral, see for instance Krishnamurthy et al. (2014), Gorton and Metrick (2012), Copeland et al. (2014). Essentially, this implies that the short/long strategy needs capital to be deployed in order to cover the haircut. Moreover, the costs of haircut based on standard assumptions of the required return on equity are high. As an example, given a 5 per cent haircut and 10 per cent required return on equity implies an additional cost of the trade equal to 50 basis point. This is around twice the size of the average CIP deviations for long-dated risk-free bonds reported in Du et al. (2019) after accounting for the lending fee, and about four times as large as the reported arbitrage return when the sovereign debt crisis in the Euro area is excluded from the sample.

Maturity According to the latest report by the International Securities Lending Association (ISLA), 79 per cent of all government bonds on-loan have open term. This means that the lender can call back the security on short notice. Although it is possible to borrow securities on longer tenors, the large number of securities with open term implies that average lending fees based on historical transactions are likely to be underestimated. The reason is that the lender has to pay (by reducing the lending fee) for the option to call back the security on short notice. Alternatively, the arbitrageur faces roll-over risk.

What are the total costs of haircut and lending fee compared to the size of the government basis? The costs of haircut is difficult to estimate as it depends on the cost of capital for the individual arbitrageur. However, by making some assumptions one can get a good sense of the magnitude of the costs. The arbitrageur may finance the haircut either by debt or equity. Some participants have limited access to bonds markets, like hedge funds, and may have to finance the haircut by equity. Others may resort to the bond market. In figure 4.6 I have calculated the cost of haircut financed at the unsecured borrowing rate for high quality financial corporations and added a lending fee of 15 basis points. Moreover, the figure also shows the cost of equity financed haircut given 10 per cent required return on equity plus the lending fee. Finally, these numbers are compared to

[40] See table OA.V in the online appendix for an overview.

the 5-year government bond basis for the three currency pairs in my analysis. One may think of the two financing alternatives as a lower and a higher end estimate of the shorting costs. Figure 4.6 illustrates that the government basis across all currencies are generally below the higher end estimate, and that the basis for GBP/USD and EUR/USD have been below the lower end estimate after 2013. Hence, it seems difficult to reap any profits for most arbitrageurs based on the short/long strategy when the costs of haircut and the lending fee are taken into account.

To sum up, the short/long trade exposes market participants to substantial non-regulatory costs that prevent market participants to take advantage of the government bond basis. This point is substantiated by the fact that the government bond basis is currently not particularly large compared with the pre-crisis period.

4.6.2 Real money investors, portfolio allocation and arbitrage

Haircut and lending fees make it costly to trade the government bond basis without being in possession of an inventory of government securities. However, these costs are not occurring for real money investors with portfolios consisting of USD securities or USD cash. A negative 5-year government bond basis between USD and JPY, for instance, indicates that anyone with a 5-year US government bond can increase their return by selling this bond, lend the USD in the FX swap market for 5 years and invest the proceeds in a 5-year Japanese government bond.

Based on Figure 4.5 it is difficult to explain the unwillingness of US government bond and cash holders in USD to reallocate into Japanese government bonds by stricter regulation or short-selling costs. There must be other reasons for the preference for US government securities. Although any attempts to explain the preference for U.S. securities necessarily are speculative, specific features of key real money investors may be part of an explanation for the reluctance to fully profit from the government bond basis. First, many real money investors with USD assets have USD liabilities and/or liquidity requirements in USD. An example is a mutual fund facing redemptions in USD. This fund may hold US government bonds exactly because of the ability to convert these into USD cash at short notice. A synthetic USD position is not a liquid asset in USD. Second, some asset managers, like money market funds, are prohibited from investing in foreign currency or do not have the operational capacity to conduct FX swap transactions. Third, government institutions like central banks and foreign governments may strategically prefer USD liquidity due to its status as the main reserve and settlement currency in the world. Even many non-US banks prefer to keep much of their liquid assets in USD. The financial crisis clearly illustrated how important USD liquidity becomes in crisis times and USD liquidity act as an insurance against liquidity squeezes in USD.

Several explanations for the existence and persistence of the government bond basis beyond those mentioned above may exist. Despite that the government bond basis easily can be taken advantage by real money investors equipped with US government bonds or USD cash, investors seem to prefer USD assets over synthetic USD assets. The access to USD liquidity US government bonds are giving the investors together with the prominent role of USD in the global financial system may be an important factor for these preferences.

4.7 CIP arbitrage with marginal funding

In this section I investigate the returns from an alternative cross currency trading strategy. This strategy implies rasing unsecured funding in one currency, investing in a risk-free asset in another currency and simultaneously hedge the foreign exchange rate risk and can be interpreted as incorporating the cost of Funding Value Adjustment (FVA), see Andersen et al. (2019).[41] To this end, I exploit the bond prices for high-quality financial institutions to calculate the return from such a cross currency arbitrage strategy. High-quality (AA) financial institutions have among the lowest funding costs in the market and should therefore overestimate the return for most market participants.

The cross currency arbitrage trade can be illustrated as follows:

$$arbprofit = \left(1 + g_{\$}^{b}\right) - \frac{F^{b}}{S^{a}}\left(1 + y_{\star}^{a}\right) \tag{4.15}$$

$$arbprofit = \left(1 + g_{\star}^{b}\right) - \frac{S^{b}}{F^{a}}\left(1 + y_{\$}^{a}\right) \tag{4.16}$$

where $g_{\$}^{b}$ is the US government bond rate, $y_{\star}^{a}$ is the foreign currency corporate bond rate, $g_{\star}^{b}$ is the foreign currency government bond rate and $y_{\$}^{a}$ is the US corporate bond rate. The superscripts a and b symbolize ask and bid rates, respectively.

Figure 4.7 illustrates the arbitrage profit for Euro, GBP and JPY using USD as base currency. The maturity is 5 year. I include both directions in the graph meaning that each line in the graph may either represent borrowing in USD and investing in foreign currency or borrowing in foreign currency and investing in USD. The funding costs are based on corporate bond prices for AA financial institutions, while government bonds are used in the investment leg.[42] The line closest to zero in the graph is the return from borrowing in USD and investing in Japanese government bonds. This line has briefly crossed zero, but the maximum profit is not more than 4 basis points. Basically, this graph illustrates that bond and FX-swap prices have been consistent with the no-arbitrage CIP condition for this maturity.

Table 4.4 depicts the arbitrage profit across three main maturities, 2, 5 and 10 years. As before, senior corporate bond prices for bonds of high quality (AA) issued by financial institutions are

[41] FVA is basically an adjustment for the underlying funding cost. The FVA has become highly debated as banks started to report large FVA connected to the derivative book. FVA is typically related to uncollateralized derivatives with customers where the bank has hedged the risk in the interdealer market. If the customer is out-of-the money (and the bank is out-of-the money on the hedge), the bank has to pay margins without receiving margin payments from the customer. This has to be financed to a rate that is higher than what the bank receives on the margin account. In the case of the arbitrage strategy in this paper, the analogy is simply that the true funding cost has to be accounted for.

[42] Due to the use of zero coupon rates in the government bond market are based on mid-rates, the calculation does not account for bid/ask spreads in government bonds. This means, however, that the arbitrage profit reported in table 4.4 is biased upwards. The bid/ask spreads in government bonds are generally small.

used as a proxy for unsecured funding costs. As can be gleaned from the table, the average and median arbitrage profit is negative for all strategies independent of the funding currency. The most interesting figures, however, are the maximum value and the number of days with positive arbitrage profit. These figures reveal whether the mean/median hide periods of positive arbitrage profits. For the 10-year maturity arbitrage profit is not possible to reap. For the 5-year maturity, borrowing in USD and investing in JPY is the only trade that provides a small number of days in arbitrage (7 out of 2007) with a limited maximum arbitrage of 4 basis points. Turning to the 2-year maturity, USD borrowing invested in JPY shows a maximum of 22 basis points. The number of days in positive arbitrage return territory is now 195, close to 10 per cent of the observations. However, the average profit during days with arbitrage opportunities is only 5 basis points (not reported). For the rest of currencies no arbitrage profit is available. The main picture is that arbitrage profit is very difficult to reap across major bond markets.

4.8 Conclusion

This paper investigates the Covered Interest Parity condition for three long-dated fixed income securities across different tenors and currencies. All these securities - Libor swaps, corporate bonds and government bonds - are commonly used to test the validity of CIP.

I explain that the Libor basis, which is the difference between the synthetic and the direct Libor swap rate at a predefined tenor, cannot be arbitraged due to the roll-over and credit risk such a strategy embeds. My results indicate that the Libor basis can be explained by relative central bank balance sheets and benchmark rate discrepancies. Central bank balance sheet policies affect the price of locking in funding over longer periods - the term funding liquidity premium - in the respective currency and consequently the costs of obtaining funding for market participants. When the term funding liquidity premium varies across currencies, the Libor basis is basically an expression of this difference.

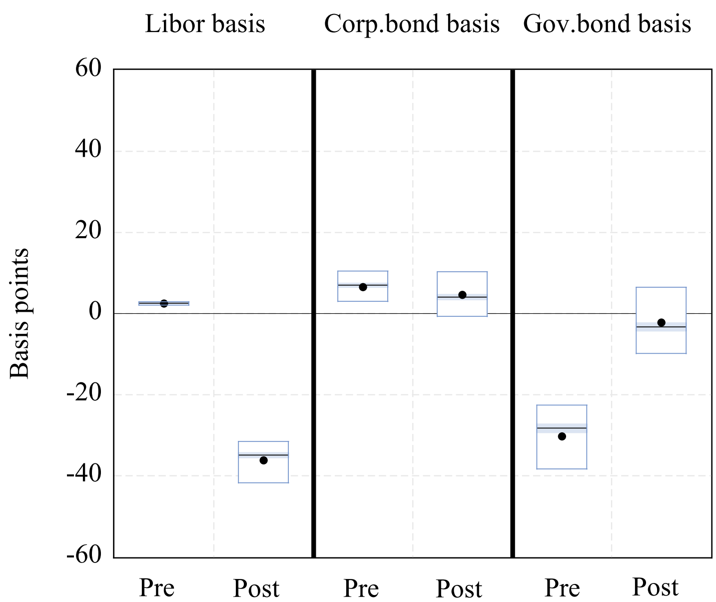
Corporate bonds do not face the issues of roll-over risk that colludes the Libor basis. This means that the corporate bond basis should be significantly closer to zero than the Libor basis after the global financial crisis when the term funding liquidity premium has varied across currencies. Indeed, I show that the corporate bond basis is smaller and much less persistent than the Libor basis in the post-crisis period. However, investments in corporate bonds are risky. Hence, trading the corporate bond basis is not riskless.

To avoid the default risk embedded in corporate bonds, I also examine cross currency deviations in government bonds. Based on a sample dating back to 2000 I show that the government bond basis is not particularly large compared to the pre-crisis period. I provide evidence suggesting that the government bond basis may be non-zero due to substantial costs (haircuts and lending fees) of taking advantage of this basis for round-trip arbitrageurs. Moreover, the observation that the government bond basis deviated substantially from zero prior to the financial crisis speaks against the common view that tighter banking regulation is the main driver of the current deviations.

Finally, I calculate the return based on an alternative arbitrage strategy and find no evidence of large and persistent arbitrage opportunities in bonds based on this measure. Overall, my results suggest that Covered Interest Rate Parity holds equally well in bond markets now as prior to the global financial crisis. Moreover, In contrast to the existing literature, I find little evidence of loss of market efficiency in the aftermath of the introduction of new banking regulation.

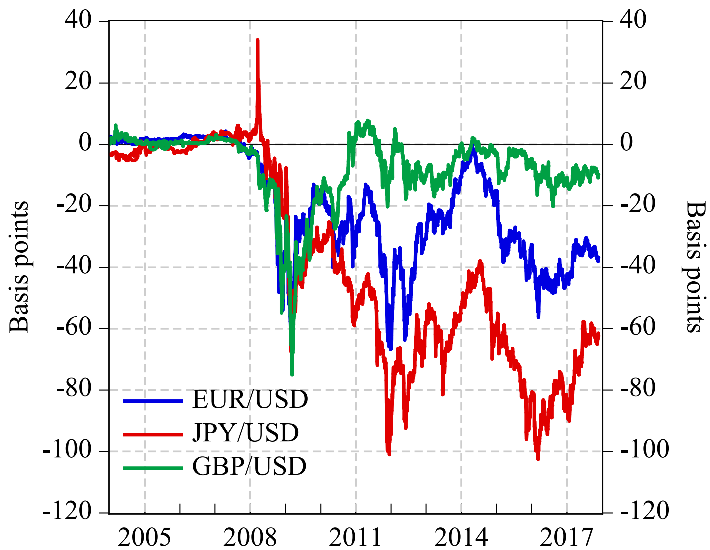
Figures and Tables

Figure 4.1
Deviations from CIP before and after the global financial crisis (EUR/USD)



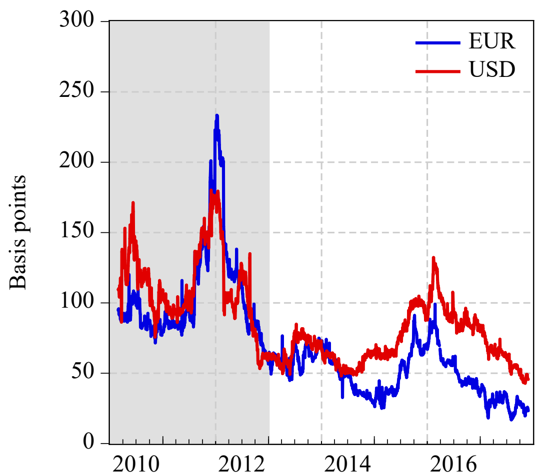
Note: The graph depicts a boxplot of the 5-year Libor basis, corporate bond basis and government bond basis for EUR/USD in two tranquil periods prior to the financial crisis(Pre=2004-2006) and after the global financial crisis (Post=2015-2017). The figure shows median (black horizontal line), average (dot), and ranges between the 25 per cent and 75 per cent quantiles (box). The corporate bond basis is calculated based on zero coupon bonds of high quality (AA) issued by financial institutions. The Government bond basis is calculated based on US and high quality European government zero coupon bonds (AAA). The Libor basis is the deviations from CIP using on Libor interest rate swaps. Negative values indicate that the US denominated security yields lower return (higher price) than the European denominated security swapped into USD, i.e. after the exchange rate risk is fully covered.

Figure 4.2
The 5-year Libor basis

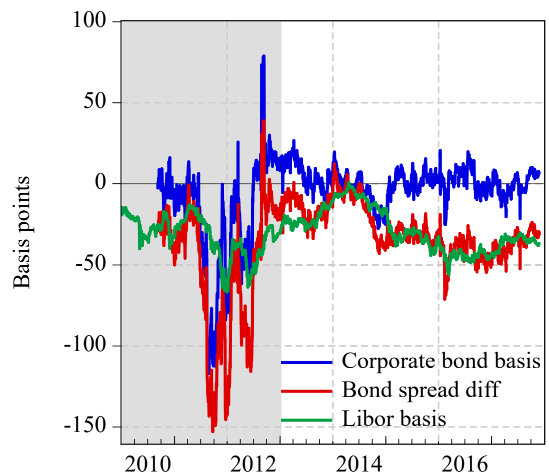


Note: The graph shows the 5-year Libor basis for three currencies - EUR, JPY and GBP - against the USD. The series are showing mid prices extracted from Bloomberg. A negative value means that the direct Libor swap rate in USD is lower than the synthetic Libor swap rate based on foreign currency.

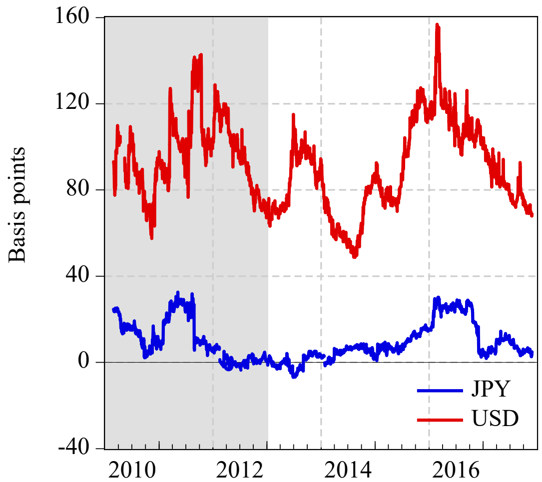
Figure 4.3
Bond spreads and the Libor basis, 5-year maturity



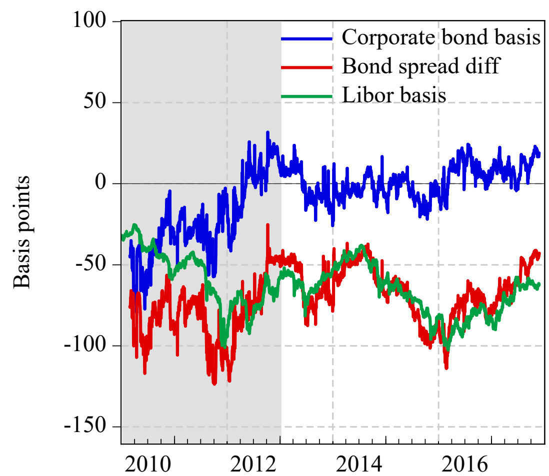
(a) Bond spreads in EUR and USD



(b) Corporate bond basis EUR/USD



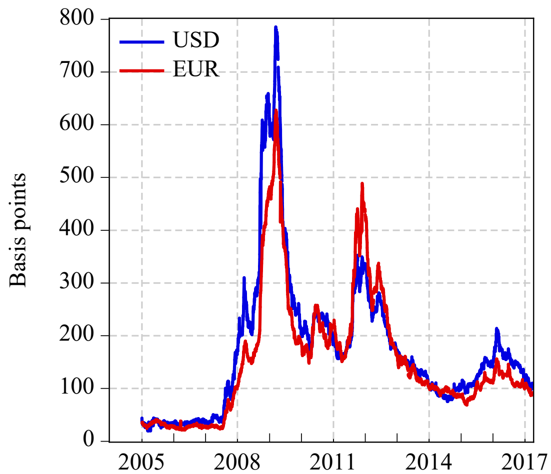
(c) Bond spreads in JPY and USD



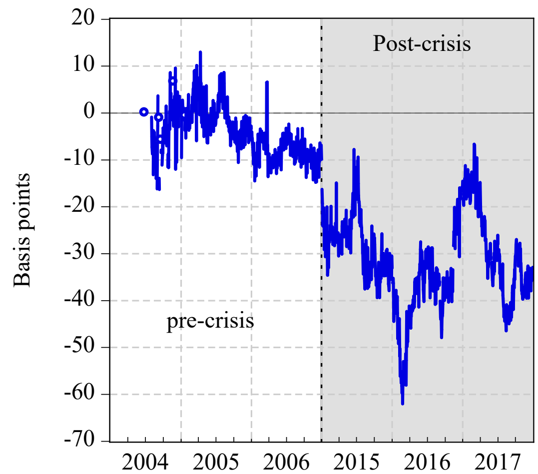
(d) Corporate bond basis JPY/USD

Note: The left-hand graphs (a and c) show the corporate bond spread for a basket of corporate issuers with the same rating and domiciled in the same country in EUR, JPY and USD. The right hand graphs (b and d) show i) the corporate bond spread differential (EUR or JPY minus USD) based on the corporate bond spreads depicted in graph a and c, ii) the Libor basis which is the difference between the synthetic and direct Libor swap rate, and iii) the corporate bond basis for similar issuers which is the difference between synthetic and direct corporate bond rate. Negative values of the basis mean that the direct corporate bond rate in USD is lower than the synthetic corporate bond rate implied from foreign currency denominated bonds. The corporate bond basis is zero if the Libor basis and the bond spread differential are equal. The shaded area illustrates the European sovereign debt crisis from 2010 to 2012. Similar graphs for GBP can be found in figure OA.2 in the online appendix.

Figure 4.4
Bond spreads



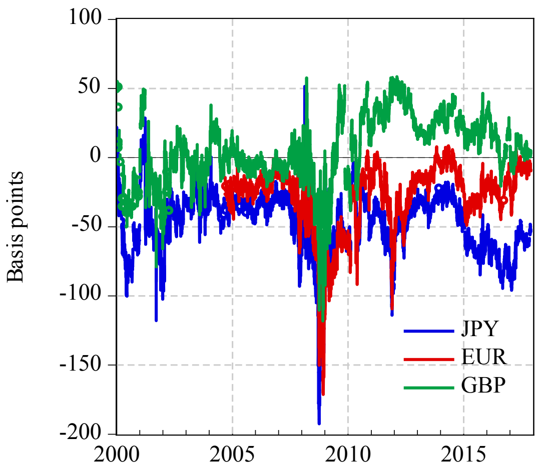
(a) Bond spreads in EUR and USD



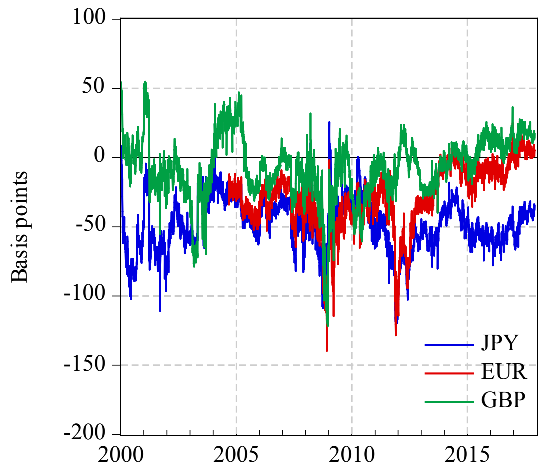
(b) Zooming in on differences in bond spreads

Note: The left-hand graph shows corporate bond spreads - the difference between the senior corporate bond rate and the Libor swap rate - for investment grade financial issuers in EUR and USD. The bond rates are from Barclays Bloomberg indices (LEEFYW for EUR and LUAFYW for USD). The right-hand graph zooms in on the difference between the two bond spreads (EUR minus USD) in the period leading up to the financial crisis (2004-2006) and the tranquil period after financial crisis (2015-2017), the grey shaded area. Negative values mean that EUR spreads are lower than the corresponding spread in USD.

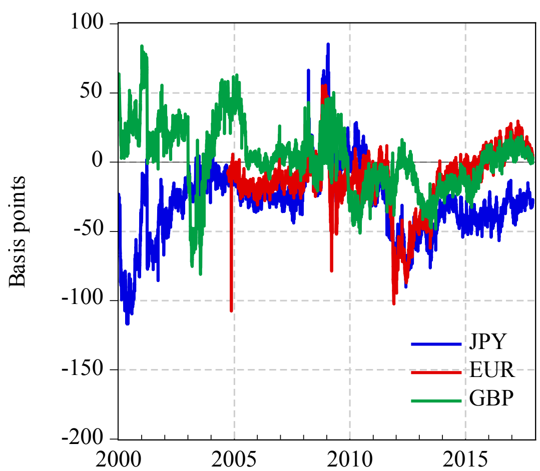
Figure 4.5
Cross currency deviations in international government bond markets



(a) 2 year maturity



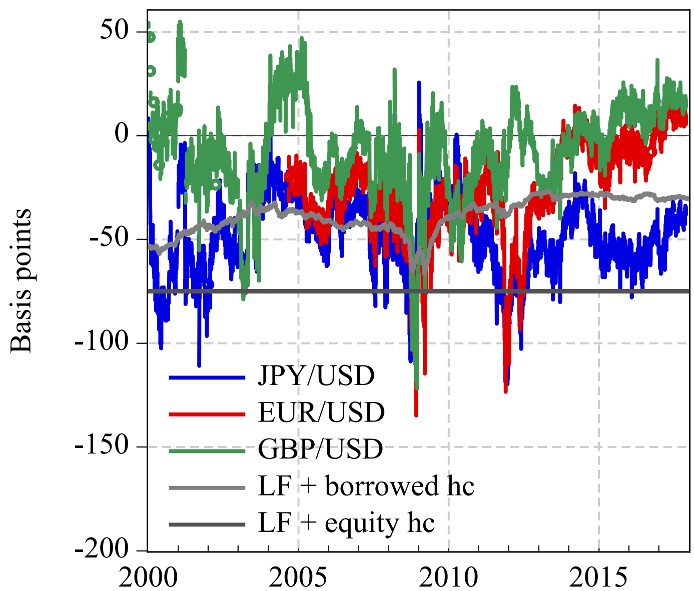
(b) 5 year maturity



(c) 10 year maturity

Note: The figure shows the difference between the direct and the synthetic US dollar government bond rates for 2, 5 and 10-year maturity, respectively. The synthetic yields are implied from EUR, GBP and JPY government bond yields. Negative values of the basis mean that the direct government bond rate in USD is lower than the synthetic government bond rate implied from foreign currency denominated bonds. For the euro area the government bond yields are based on government issuers with AA and AAA rating. The government bond basis is calculated based on mid prices. The government bonds are zero-coupon interest rates collected from either Bloomberg or central bank webpages.

Figure 4.6
Estimated costs of round-trip arbitrage: lending fee and haircut



Note: The figure shows the government basis for JPY/USD, EUR/USD and GBP/USD together with the total costs of a 15 basis point lending fee (LF) and two different ways of financing a 5 per cent haircut: i) borrowed financing based on unsecured borrowing costs in USD obtained from Bloomber/Barclays US aggregate index for financial corporations (LF+borrowed hc), and ii) equity financed haircut based on 10 per cent required return on equity (LF+equity hc).

Table 4.1
Determinants of the Libor basis

	(1) 2-year	(2) 5-year	(3) 10-year
$\Delta LB_{t-1}(\beta_1)$	0.248***	0.245***	0.250***
	(3.75)	*(4.36)*	*(6.14)*
$\Delta RelCBbal(\beta_2)$	-15.75**	-14.23**	-14.77***
	(-2.47)	*(-2.17)*	*(-2.61)*
$\Delta CDSsprFR(\beta_3)$	-0.162***	-0.156***	-0.106***
	(-4.49)	*(-4.43)*	*(-3.99)*
$\Delta LIBCPdiff(\beta_4)$	-0.124***	-0.095**	-0.073***
	(-2.87)	*(-2.57)*	*(-2.81)*
$LB_{t-1}(\beta_5)$	-0.021***	-0.021***	-0.018***
	(-2.59)	*(-3.14)*	*(-3.73)*
$Constant$	-0.657***	-0.704***	-0.589***
	(-3.04)	*(-3.60)*	*(-3.96)*
$CurrencyFE$	Yes	Yes	Yes
Adj R^2	0.149	0.134	0.113
Number of Observations	1119	1119	1119

*Note: The table depicts the results from the panel regression specified in equation 4.7 for EUR/USD, GBP/USD and USD/JPY. LB is the Libor Basis, RelCBbal is the ratio between the indexed foreign central bank balance sheet and the indexed Federal Reserve balance sheet, CDSsprFR is the difference between the 5-year CDS price on France denominated in EUR and USD and LIBCPdiff is the difference between 3-month Libor CP spread in foreign currency and USD. The dependent variable is the Libor basis. Results are reported with White cross section standard errors. *** denote a statistical significance level of 1 per cent, ** 5 per cent and * 10 per cent. The sample runs from 2010 to 2017.*

Table 4.2
Vector Error Correction Model

	(a)Unrestricted					
	EUR/USD		USD/JPY		GBP/USD	
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-0.95	1	-0.97	1	-0.56
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff	-0.029	0.011	-0.025	0.011	-0.016	-0.000
t-values	(-2.92)	(4.00)	(-2.83)	(3.02)	(-4.59)	(-0.38)

	(b)Restricted: Coint. relation (1,-1)					
	EUR/USD		USD/JPY		GBP/USD	
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-1	1	-1	1	-1
LR test (prob.)	0.39		0.41		0.72	
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff	-0.028	0.011	-0.023	0.010	-0.015	-0.000
t-values	(-2.91)	(4.09)	(-2.72)	(3.01)	(-4.60)	(-0.24)

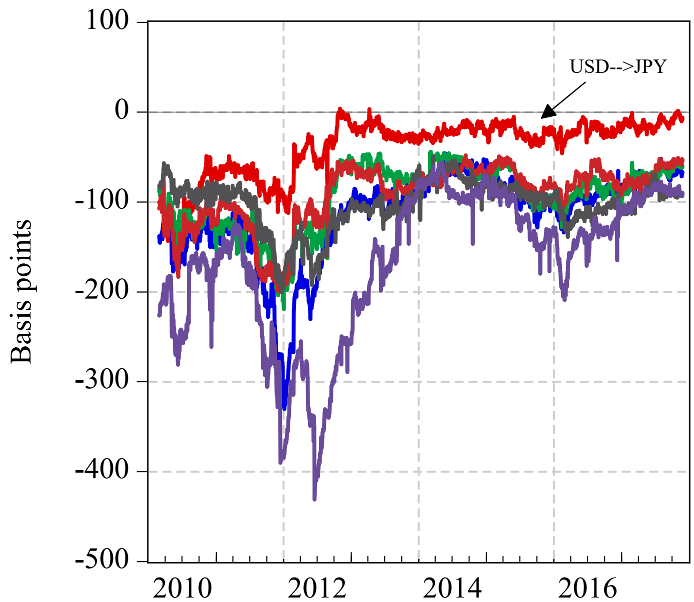
Note: The table shows the results from a Vector Error Correction Model with two lags, no trend and intercept in the cointegrating relationship. The first model is an unrestricted model (a), while in (b) the cointegrating relationship is restricted to (1,-1) The variables are 5-year bond spread differential (bspr) and 5-year Libor basis (LB). Bond spreads and the Libor basis are measured in basis points. The sample runs from January 2010 to December 2017.

Table 4.3
Lending fee and haircut in the securities lending market

	Oct 9, 2015			Nov 10, 2015			Dec 31, 2015		
	5th	Mean	95th	5th	Mean	95th	5th	Mean	95th
	a) Lending Fee (bps)								
U.S. Treasury/Agencies	5	13	31	5	15	40	6	20	60
U.S. Corporate Bonds	8	27	38	8	28	25	8	27	25
	b) Haircut (per cent)								
U.S. Treasury/Agencies	0	2	5	0	2	5	0	2	5
U.S. Corporate Bonds	2	2	3	2	2	5	2	2	5

Note: The table shows lending fees and haircut levels based on a survey of securities lenders conducted by the Office for Financial Research and New York Fed. The data are collected on three specific dates in the last quarter of 2015 and taken from Baklanova et al. (2016).

Figure 4.7
Cross currency arbitrage 5-year bonds



Note: The graph shows the deviations between the synthetic funding cost and the government bond rates for EUR, GBP, USD and JPY. The maturity is 5-year. Positive numbers indicate arbitrage. Both directions are included, i.e. from USD to foreign currency and from foreign currency to USD.

Table 4.4
Arbitrage profit in bonds

	(1)	(2)	(3)	(4)	(5)	(6)
	$–>EUR	$–>JPY	$–>GBP	EUR–>$	JPY–>$	GBP–>$
			10-year maturity			
Mean (bps)	-125	-77	-113	-131	-100	-169
Median (bps)	-108	-60	-100	-1.18	-96	-170
Max (bps)	-66	-25	-51	-46	-53	-71
Obs	1932	1918	1896	1687	2009	1314
Arb days	0	0	0	0	0	0
			5-year maturity			
Mean (bps)	-92	-39	-94	-114	-103	-142
Median (bps)	-81	-25	-84	-99	-97	-113
Max (bps)	-48	*4*	-44	-46	-49	-52
Obs	2010	2007	2006	2012	2012	2011
Arb days	0	7	0	0	0	0
			2-year maturity			
Mean (bps)	-58	-24	-80	-98	-62	-119
Median (bps)	-52	-20	-71	-87	-59	-82
Max (bps)	-21	*22*	-37	-41	-5	-17
Obs	2006	1997	1974	2012	2012	2012
Arb days	0	195	0	0	0	0

Note: The table illustrates the arbitrage profit for three maturities based on actual funding cost in the funding currency and risk-free investment in government bond in investment currency. All figures are in basis points. USD–>EUR means that the funding currency is USD and investment currency is euro while EUR–>USD illustrates the case where euro is the funding currency and USD is the investment currency. Positive figures imply arbitrage opportunities. Bid/ask spreads are taken into account. The sample runs from january 2010 to December 2017.

Appendix

4.A Data and calculations

Table 4.A.1
Summary statistics

	A. Libor basis			B. Rel. CB balance sheets			C. Benchmark and CDS spreads			
	EUR	GBP	JPY	EUR	GBP	JPY	EUR	GBP	JPY	CDS USD-FRA
Mean	-29.95	-7.19	-63.45	0.81	1.13	1.29	15	5	20	23
Median	-30.96	-8.21	-63.62	0.85	1.09	1.06	10	3	13	15
Maximum	0.10	6.63	-25.86	1.10	1.58	2.19	46	24	81	106
Minimum	-65.40	-26.44	-101.63	0.54	0.66	0.85	1	-6	-18	3
Std. Dev.	12.90	6.21	16.66	0.16	0.22	0.42	11	6	20	21
Observations	413	413	413	413	413	413	377	377	377	391

Note: The maturity of the Libor basis is 5 years. The benchmark spread is the U.S. Libor minus the foreign currency equivalent benchmark rate with the foreign currency denoted in the column heading. The last column depicts the 5-year CDS spread between Germany and France. All numbers in basis points except the relative central bank balance sheets (Rel. CB balance sheets) which are indexed at 1 in January 2010. The sample runs from 2010 to 2017. Weekly data frequency.

Data sources and bond spreads

1. *Libor Basis/Cross Currency Basis Swap with 3m IBOR as underlying short rate*: Quoted on Bloomberg with tickers EUBSx, JYBSx, BPBSx, where x the number of years to maturity.

2. *Commercial paper rates*: Commercial paper rates from Tradeweb for A1/P1 rated financial institutions. Quoted on Thomson Reuters Eikon with tickers: YUSD3MCPF=TWEB, YGBP3MCPF=TWEB, Y3JPYMCPF=TWEB and YEUR3MCPF=TWEB.

3. *Interbank Offered Rates - IBOR*: Quoted on Bloomberg with tickers EUR003M, BP0003, JY0003 and US0003.

4. *Iterest Rate Swaps*: Interest rate swap rates with 3m IBOR as underlying short rate. Quoted on Bloomberg with tickers JYSWx (for Japanese Yen 6m LIBOR is the underlying short rate), EUSWxV3, USSWx, BPSWx, where x represents the number of years to maturity.

5. *Government bond yields*: Estimated (Nelson Siegel approach) zero coupon rates downloaded from Bank of England webpage and European Central Bank webpage. For US and JPY government bonds I use data sourced through Bloomberg with tickers GS x (generic strips) and ticker GJGBx, respectively. x represents the number of years to maturity.

6. *Bank balance sheet data*: Available at the respective central bank webpages.

7. *Central Bank balance sheet data*: Available at Bloomberg with tickers EBBSSECM, B111B56A, BJACTOTL and FARBAST.

8. *Credit Default Prices prices for France*: Quoted on Thomson Reuters Eikon with tickers FR5USD and FR5EUR.

9. *Corporate bond data*: The computation of corporate bond spreads follows the following steps:

    (a) Extract all individual bonds included in Barclays Global Aggregate Index (Bloomberg ticker for information about the index: LEGATRUU) issued by an institution classified as "banking" and issued by institutions domiciled in Germany, Netherlands, Australia, Canada, UK, and Japan and where the issuances are denominated in USD, EUR, GBP or JPY. Bonds included in the Global Aggregate index have an amount outstanding of at least 300mn USD or EUR, 200mn GBP, 35bn JPY.

(b) Select Senior unsecured issues (bullet bonds) with rating AA or A1.

(c) Calculate the zero coupon spread over the respective currency interest rate swap curve. I follow the calculation of bond spreads in Du et al. (2019) closely. The bond pays a coupon (*coup*), q times a year. The investor receives the principal at $t+n$. Each coupon and principal payment are discounted with the term structure of the zero coupon Libor swap rates (interest rate swap rates), $c_{t,t+n}^{j,LibSwap}$. The bond spread is defined as $b_{t,t+n}^{j}$, i.e. the spread over the Libor swap rate necessary to achieve the observed price $P_{t,t+n}^{j}$ in currency j. The procedure can be expressed as follows:

$$P_{t,t+n}^{j} = \sum_{\tau=1/q}^{n} \frac{coup}{(1+c_{t,t+n}^{j,LibSwap}+b_{t,t+n}^{j})^{\tau}} + \frac{1}{(1+c_{t,t+n}^{j,LibSwap}+b_{t,t+n}^{j})^{n}} \tag{4.17}$$

(d) The average bond spread is calculated for each rating category, maturity bucket (1.5-2.5 years to maturity equals maturity bucket 2 year etc.), country of incorporation of the issuer and currency.

(e) The bond spread differentials are calculated for the same rating category, maturity bucket and country of incorporation separately. For instance, the n-year bond spread differential between Japanese issuers in JPY and USD with rating A1 is:

$$BondSprdDiff = b_{t,t+n}^{JPY,A1} - b_{t,t+n}^{USD,A1} \tag{4.18}$$

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4.B The relation between funding liquidity and central bank balance sheet policies

The central bank has the power to inject the most liquid asset in the monetary system - central bank reserves. Asset purchases, which effectively inject central bank reserves, may affect the funding liquidity through different channels. One of these is the bank balance sheet channel. This channel is a direct product of the central bank purchasing securities held by the non-bank sector.[43]

Figure 4.B.1 provides a stylized illustration of how this channel works. For simplicity the central bank has a clean balance sheet before embarking on asset purchases. For simplicity, the aggregate

[43] See also Christensen and Krogstrup (2016) for an explanation of this mechanism.

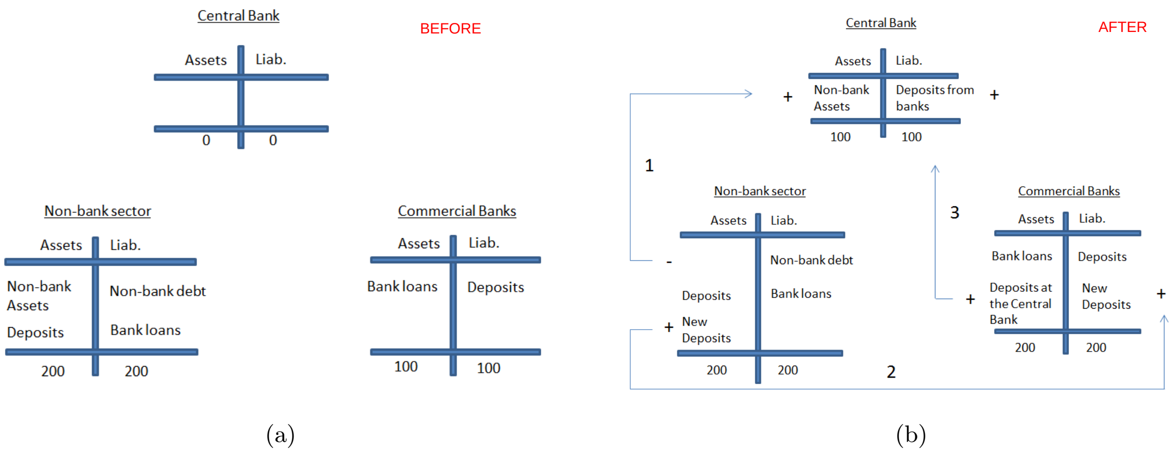
private bank balance sheet consists of bank loans and deposits. The non-bank sector holds non-bank assets and commercial bank deposits financed by bank debt and non-bank debt. As the central bank absorbs assets held by non-banks (1), it requires commercial banks to credit the non-bank client's deposit account as settlement for the assets the central bank has purchased (2). On the other side, the commercial bank simultaneously requires central bank reserves in return from the central bank. This leads to an increase in banks' deposits at the central bank (3). In figure 4.B.1, the central bank buys securities worth 100 from non-banks. For the non-bank sector, the transaction with the central bank is no more than an asset swap - securities in return for bank deposits. In contrast, the aggregate bank balance sheet increases by 100 - new deposit on the liability side and highly liquid central bank reserves on the asset side and the balance sheet size remain unaffected. The central bank has increased its balance sheet size by 100. The increase in banks' central bank reserves leads to an increase in liquid assets for banks, while the increase in non-bank deposit liabilities increase banks' deposit-to-illiquid asset ratio.

The illustration is highly simplified, but serve as an example of how central bank asset purchases may affect commercial banks balance sheets on the margin. The impact on banks' funding position depends on which type of deposits the banks receive, how large share of the new liabilities that ends up as deposits, what kind of alternative liabilities banks may receive and the maturity structure of these liabilities. However, on the margin at which the new liabilities created by the central bank will put downward pressure on the yields banks are willing to attract funding and increases the availability of term funding. This may be especially pronounced in situations with sluggish domestic growth in banks' illiquid assets.

In short, if the additional deposits - or liabilities - are characterized as long term-funding (i.e retail deposits are regarded as long-term funding (Drechsler et al. (2017))) central bank asset purchases contribute both to a more liquid banking system *and* additional long-term funding for banks. When the central bank creates new long-term bank liabilities through asset purchases over and above the ex-ante demand by the banking sector for such liabilities, funding liquidity improves and the yield on long-term bank liabilities falls. Basically, this particular channel implies that banks can access long-term funding at favourable terms either by replacing bond issuances with deposits and/or attracting market based funding (by issuing bonds) at relatively low spreads. The increase in central bank induced liabilities is disconnected from the standard bank-driven increase in liabilities facilitated by non-cash asset growth. The new liabilities are instead matched by highly liquid central bank reserves. As shown in Figure 4.B.2, data indicate that this channel has indeed been at play.

The deposit-to-asset ratio may, however, increase independently of asset purchases. A change in the composition of liabilities can be driven by several factors. Negative interest rates may for instance induce a shift from market-based money market investments to deposits as it is difficult for banks to charge negative interest rates on household deposits. However, figure 4.B.2 depicts a remarkable correlation between the introduction of asset purchases and relative deposit growth, potentially reinforced by the introduction of negative interest rates.

Figure 4.B.1
Asset purchases and the bank balance sheet channel



Note: Panel a) depicts a stylized illustration of the aggregate players' balance sheets before the central bank has initiated asset purchases. In panel b) the central bank is buying securities from the non-bank sector worth 100 (1). Simultaneously, the non-bank sector gets bank deposits on its asset side (2) and commercial banks get deposits at the central bank (3). Both the central bank and commercial banks have increased their balance sheet, while the non-bank sector's balance sheet is unchanged.

The central bank may also purchase securities held by commercial banks. In such case, asset purchases can affect banks' asset composition and can potentially explain the correspondence between central bank asset purchases the relative increase in deposits. Although banks' total assets will not change, the share of cash relative to non-cash assets will increase. Figure 4.B.2 depicts assets excluding cash holdings. However, this can not explain the increase in deposits. When the central bank purchases assets held by banks, non-cash assets fall, but deposit liabilities are not affected.

There are also other ways asset purchases may affect funding liquidity. For instance the portfolio rebalancing channel may improve funding liquidity. The argument is that when the central bank buys a certain asset the seller seeks for alternative investments in other asset classes. This may be reinforced by extraordinary low yield on long-dated securities that often is the case when unconventional monetary policy is implemented.

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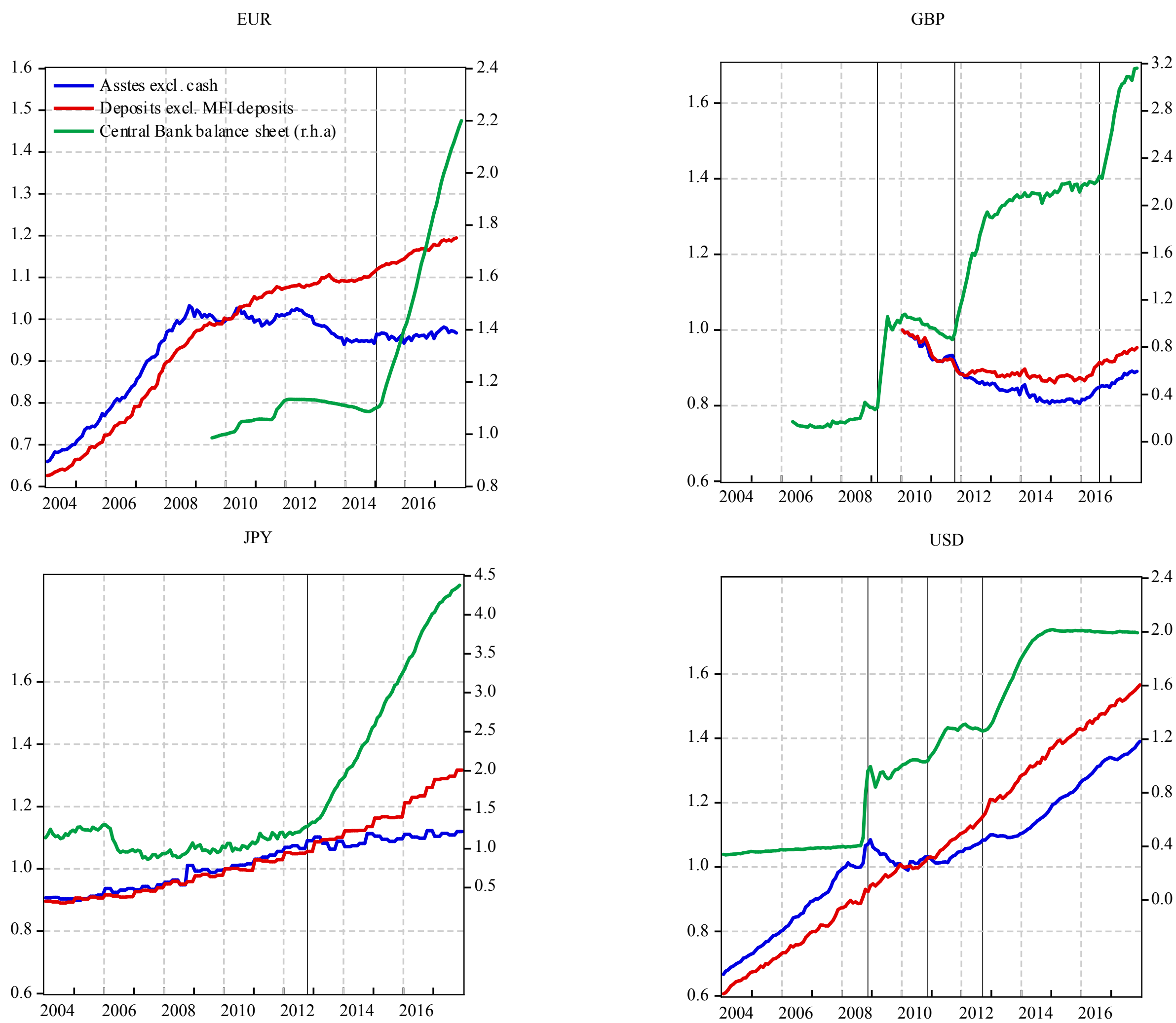
Figure 4.B.2
Banks' assets and deposits



Note: The graph shows private banks' assets excluding cash in the central bank, deposits excluding deposits from Monetary Financial Institutions (interbank deposits) and the size of the central bank balance sheet in EUR, GBP, JPY and USD. All series are indexed to 1 at the beginning of 2010. The central bank balance sheet in EUR represents only the asset purchases due to the fact that the ECB has conducted a large range of open market operations. These operations have affected the size of the balance sheet, but are not relevant for the deposit channel. For the remaining currencies I use aggregate data on the central banks balance sheets. The vertical lines indicate the dates when the respective central banks embarked on large-scale asset programs.

Supplementary Internet Appendix to accompany

Covered Interest Parity in long-dated securities

4.C Benchmark rate discrepancies

Unsecured term interbank reference rates all have one common problem: They are meant to represent rates on transactions that are virtually non-existent. Available data and surveys show that unsecured interbank lending is heavily concentrated in the shortest maturities, like overnight. Very little unsecured interbank lending goes on in maturities of 3 and 6-months.[44] This was the case even before the financial crisis, and the trend has been reinforced since then. This means that the banks submitting ibor-rate must rely on rates from other markets with similar characteristics, on their subjective judgement or a combination of the two. The current effort in many countries to produce nearly risk-free alternative reference rates must be seen in this context.

Since 1998, Libor has been defined by the panel banks' daily answer to the following question: "At what rate could you borrow funds, were you to do so by asking for and then accepting interbank offers in a reasonable market size just prior to 11 am?" This question is posed in a way that defines Libor as an interbank offered rate. However, recognizing the fact that interbank term transactions are rare, the administrator of Libor, ICE Benchmark Administration Limited (IBA), has laid out a roadmap for the transition of Libor to a new "waterfall methodology". This methodology entails a new output statement for Libor: "A wholesale funding rate anchored in LIBOR panel bank" unsecured transactions to the greatest extent possible, with a waterfall to enable a rate to be published in all market circumstances".

The term "waterfall" refers to the ordering of inputs for the submissions into three levels. To the extent available, panel banks should base their submissions on Level 1 input, which are "eligible wholesale, unsecured funding transactions". If no such eligible transactions were made, submissions should be transaction-derived (Level 2). That means utilizing time-weighted historical eligible transactions adjusted for market movements, and linear interpolation. If neither Level 1 nor Level 2 inputs are available, panel banks should base their submissions on expert judgement (Level 3).

One important feature of the new methodology is that the eligible transactions are no longer limited to interbank loans. The eligible transactions are rates paid by banks on unsecured term deposits, as well as fixed rates paid on primary issuances of commercial paper (CP) and certificates of deposits (CD). The major part of CP and CD funding comes from investors outside the banking system, like money market funds and non-financial corporations. Rates paid by banks on CP/CD funding are not interbank rates and cannot necessarily be seen as offered rates like in the current definition of Libor. Hence, the âIBOâ part of the abbreviation Libor will no longer apply. In general, funding rates from counterparties outside the banking system are likely to be somewhat lower than rates on interbank loans. The reason is that money market funds and corporations that supply funding to banks via CP/CD are not subject to the same regulatory requirements as a bank lending to another bank. Thus, all else equal, the price of funding from outside the banking system will be somewhat cheaper than interbank funding.

[44] See for instance Euro Money Market Survey (2015) by the European Central Bank.

IBA expects the transition to the new waterfall methodology to be completed by no later than the first quarter of 2019. However, USD Libor already looks very similar to the rates paid for CP-funding by highly rated banks, as shown in figure OA.1. The waterfall methodology also means that even Libor, despite the same definition across currencies, can differ due differences in money market activity and judgment across currencies.

Euribor was created in 1999 with the introduction of the euro. Currently 20 banks provide their daily submissions to EURIBOR according to the following definition: Euribor is defined as the rate at which euro interbank term deposits are offered by one prime bank to another prime bank within the EMU zone, and is calculated at 11:00 am (CET) at spot value (T+2).

Euribor is thus defined as an interbank rate. In contrast to US Libor it is not only an interbank rate in name, but also quoted as one. Chart 4 below shows the same as Chart 3, only for the euro area: The difference between 3-month Euribor and the rate on 3-month commercial paper in euros issued by highly rated European banks. As discussed above, differences in regulatory costs should imply that interbank rates are somewhat higher than comparable rates on banks' borrowing from non-banks. As can be seen from chart 4, this is the case for Euribor. The difference is not constant over time. Variation may be due to many factors, like shifts in the demand-supply balance in the CP market that are not transmitted one-for-one to Euribor. On average since 2011, the spread between 3-month Euribor and the corresponding CP rate has been 12 basis points. A simple back-of-the-envelope calculation substantiates such a spread. An interbank loan is subject to a 20 per cent risk weight in Basel III. Assuming 10 per cent capital requirement and 10 per cent required return on equity, the required spread on top of the borrowing cost is 20 basis points (0.2*0.1*0.1)

Since unsecured term lending transactions between banks are rare, the panel banks' Euribor submissions must to a large extent be based on expert judgement. Panel banks' submissions reflect what they believe the rates on eligible interbank lending transactions would have been, if they had taken place. This judgement is likely to be informed by rates on traded products in other markets like CP, CD and OIS, adjusted appropriately to reflect interbank term offered rates.

Acknowledging the decline in interbank activity, the administrator of Euribor, the European Money Market Institute (EMMI), has launched a program of Euribor reform. An important part of this has been to move from a quote-based methodology to a transaction-based methodology for Euribor (the latter sometimes referred to as Euribor+). To assess whether a seamless transition from a quote-based to a transaction-based methodology would be feasible, the EMMI ran a so-called pre-live verification program from September 2016 to February 2017. During this period, the EMMI calculated a transaction-based rate based on collected data. In order for a seamless transition to be feasible, the level and volatility of the transaction-based rate would have to be similar to the level and volatility of Euribor. In May 2017, the EMMI presented the outcome of the pre-live testing. It concluded that the level and volatility of the transaction-based rate differed too much from the quote-based Euribor to allow a seamless transition. This conclusion is mirrored by the different behavior of the 3-month Euribor and corresponding rate on banks' borrowing via commercial paper in figure OA.1.

As a way forward, EMMI now plans to introduce a hybrid methodology for Euribor. EMMI recognizes that the level of liquidity in the unsecured money market is currently not consistently sufficient to base the Euribor calculation solely on transactions. In a consultation paper published in March 2018, EMMI asked market participants for feedback on the proposed hybrid methodology. In short, the suggested hybrid methodology has many similarities to the waterfall structure for Libor described above. It is suggested to follow a hierarchical approach, where inputs to Euribor submissions are divided into three levels, ranging from real-time eligible transactions to panel banks' judgement. Eligible transactions include unsecured, fixed rate, cash deposits from banks and a range of non-bank financial institutions, as well as funds obtained from all counterparties via commercial paper and certificates of deposits.

4.D Additional tables and graphs

This section provides supplementary results complementing the evidence in the main text. Table OA.I shows an alternative regression specification to the panel specification in table 4.1 applying a Seemingly Unrelated Regression framework, table OA.II illustrates the cointegrating relationship between the Libor basis and the bond spread differential, while table OA.III and table OA.IV provide the results from a Vector Error Correction Model for maturity 2 and 10 years. Table OA.V and table OA.VI illustrate the haircut levels applied by EUREX Clearing and the bid/ask spreads in the forward exchange rate market, respectively. Furthermore, figure OA.1 shows the respective IBOR rates and the A1-P2 CP rates across currencies. Figure OA.2 depicts the 5-year bond spreads and relation to the Libor basis for GBP/USD while figure OA.3 and figure OA.4 show the bond spreads and Libor basis for 2 and 10 year maturities, respectively. Finally, figure OA.5 shows the repo haircut levels source from New York Federal Reserve.

Table OA.I
Seemingly Unrelated Regression

	2-year Libor Basis			5-year Libor Basis			10-year Libor Basis		
	EUR	JPY	GBP	EUR	JPY	GBP	EUR	JPY	GBP
ΔLB_{t-1}	0.05	0.1**	0.06	0.17***	0.18***	0.20***	0.18***	0.23***	0.21***
	(1.23)	*(2.32)*	*(1.33)*	*(4.07)*	*(4.07)*	*(4.59)*	*(4.06)*	*(4.70)*	*(4.63)*
$\Delta RelCBBalSheet(FC/US)$	4.91	-16.25**	-28.53***	-48.62**	-16.36**	-19.96***	-52.22**	-16.56**	-19.26**
	(0.17)	*(-2.23)*	*(-2.89)*	*(-2.35)*	*(-2.04)*	*(-2.62)*	*(-2.51)*	*(-2.11)*	*(-2.51)*
$\Delta CDSsprFR(USD-EUR)$	-0.3***	-0.2***	-0.09***	-0.19***	-0.19***	-0.09***	-0.10***	-0.11***	-0.11***
	(-5.50)	*(-4.46)*	*(-2.84)*	*(-5.13)*	*(-4.30)*	*(-3.33)*	*(-2.85)*	*(-2.71)*	*(-4.10)*
$\Delta CP-IBORsprdiff(FC-USD)$	-0.23***	-0.24***	-0.15***	-0.10***	-0.08***	-0.09***	-0.06	-0.06**	-0.07**
	(-4.24)	*(-9.36)*	*(-4.17)*	*(-2.63)*	*(-2.78)*	*(-2.95)*	*(-1.56)*	*(-2.16)*	*(-2.57)*
LB_{t-1}	-0.02**	-0.02***	-0.05***	(-0.03)***	-0.02***	-0.04***	-0.02***	-0.02**	-0.04***
	(-2.29)	*(-2.61)*	*(-3.76)*	*(-3.39)*	*(-2.85)*	*(-3.51)*	*(-3.15)*	*(-2.55)*	*(-3.25)*
Constant	-0.56	-0.62**	-0.37***	-0.80	-1.28***	-0.24**	-0.63***	-1.11**	-0.30**
	(-1.94)	*(-2.33)*	*(-2.73)*	*(-3.22)*	*(-2.82)*	*(-2.19)*	*(-2.98)*	*(-2.54)*	*(-2.25)*
Obs.	372	372	372	373	373	373	373	373	373
System obs.		1116			1119			1119	
Adjusted $\hat{R2}$	0.13	0.14	0.08	0.17	0.12	0.11	0.12	0.1	0.13

*Note: The table depicts the results from a Seemingly Unrelated Regression for EUR/USD, GBP/USD and USD/JPY. *** denote a statistical significance level of 1 per cent, ** 5 per cent and * 10 per cent, respectively. The model specification is specified in equation 4.7. The results depict a similar picture as the panel regression results. The currency specific coefficient estimates on the CDS-spread and the benchmark spread are slightly higher for EUR and JPY (and lower for GBP) than the common coefficients from the panel regression, especially for the 2-year basis swap. However, by translating the coefficients into the impact of one standard deviation change in the relative central bank balance sheets the effects are comparable across currencies and very similar to the panel regression results. The differences in the coefficients are related to the fact that the balance sheets are indexed and the base level varies across currencies. The sample runs from 2010 to 2017.*

Table OA.II
Johansen Cointegration test

	EUR/USD		USD/JPY		GBP/USD	
	Coint.rel.	P-value	Coint.rel.	P-value	Coint.rel.	P-value
Trace	None	0.00	None	0.00	None	0.00
	At most 1	0.85	At most 1	0.77	At most 1	0.10
Max E.V	None	0.00	None	0.00	None	0.00
	At most 1	0.85	At most 1	0.77	At most 1	0.10

Note: Cointegration test for the 5-year Libor basis and the 5-year bond spread differential for high quality issuers. I include two lags based on Schwarz Information Criterion.

Table OA.III
Vector Error Correction Model - 2 year maturity

	EUR/USD		USD/JPY		GBP/USD	
			(a)Unrestricted			
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-0.76	1	-0.97	1	-0.53
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff $((\lambda_{bspr}),(\lambda_{LB}))$	-0.05	0.005	-0.004	0.005	-0.025	-0.00027
t-values	(-3.57)	(1.84)	(-0.99)	(2.52)	(-3.15)	(-0.13)
			(b)Restricted: Coint. relation (1,-1)			
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-1	1	-1	1	-1
LR test (prob.)	0.009		0.82		0.22	
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff $((\lambda_{bspr}),(\lambda_{LB}))$	-0.03	0.002	-0.004	0.005	-0.02	0.0002
t-values	(-2.87)	(1.28)	(-0.95)	(2.52)	(-2.90)	(0.11)

Note: The table shows the results from a Vector Correction Model with two lags, no trend and intercept in the cointegrating relationship. The variables are the 2-year corporate bond spread differential (bspr) in EUR, JPY and GBP, against USD and the 2-year Libor basis (LB). The first model is an unrestricted model (a), while in (b) the cointegrating relationship is restricted to (1,-1). Bond spreads and the Libor basis are measured in basis points. The sample runs from January 2010 to December 2017.

Table OA.IV
Vector Error Correction Model - 10 year maturity

	EUR/USD		USD/JPY		GBP/USD	
			(a)Unrestricted			
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-1.59	1	-1.27	NA	NA
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff $((\lambda_{bspr}),(\lambda_{LB}))$	-0.012	0.002	-0.004	0.0014	NA	NA
t-values	(-3.00)	(2.9)	(-1.70)	(2.21)	(NA)	(NA)
			(b)Restricted: Coint. relation (1,-1)			
	bspr	LB	bspr	LB	bspr	LB
Coint. Coeff	1	-1	1	-1	NA1	NA
LR test (prob.)	0.056		0.30		NA	
	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB	$\Delta bspr$	ΔLB
Adj. coeff $((\lambda_{bspr}),(\lambda_{LB}))$	-0.010	0.0013	-0.004	0.0010	NA	NA
t-values	(-2.91)	(2.37)	(-1.83)	(1.86)	(NA)	(NA)

Note: The table shows the results from a Vector Correction Model with two lags, no trend and intercept in the cointegrating relationship. The variables are the 10-year corporate bond spread differential (bspr) in EUR, JPY and GBP, against USD and the 10-year Libor basis (LB). The first model is an unrestricted model (a), while in (b) the cointegrating relationship is restricted to (1,-1). Bond spreads and the Libor basis are measured in basis points. The sample runs from January 2010 to December 2017. The estimates for GBP/USD is not available due missing data.

Table OA.V
EUREX Clearing cross currency haircut levels

Base currency	Cross currency	Cross currency haircut
USD	AUD	8.40 %
USD	CAD	5.00 %
USD	CHF	6.30 %
USD	EUR	4.30 %
USD	GBP	5.60 %
USD	JPY	4.20 %
USD	NZD	7.40 %

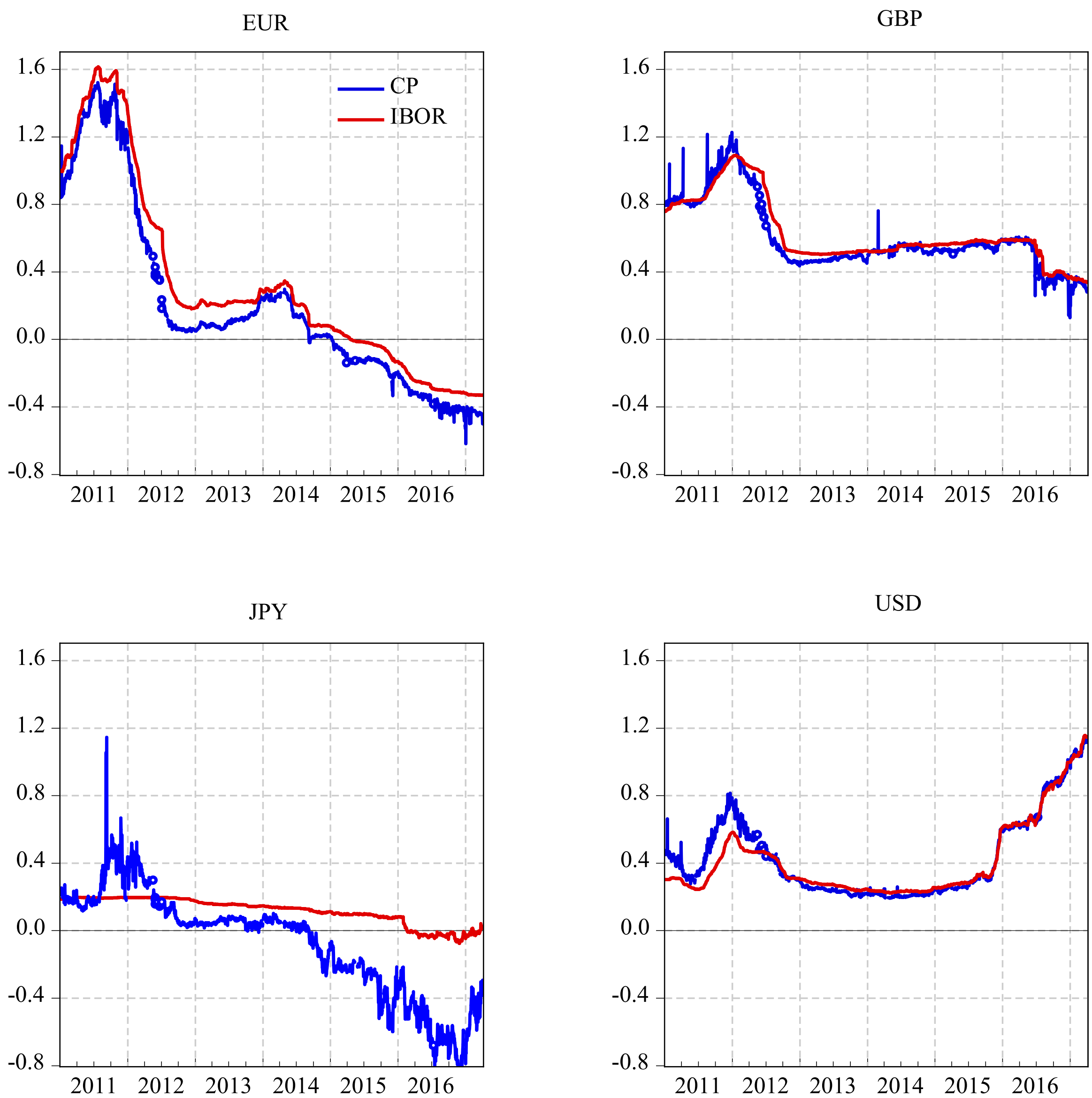
Note: The table shows the haircut applied by Eurex clearing - a large European clearinghouse - in the case of cross currency collateral. The numbers are updated by Eurex regularly. The numbers indicate a haircut level between 4 and 9 per cent depending on the currency pair. This indicates the additional risk connected to cross currency collateral. Source: EUREX Clearing.

Table OA.VI
Bid/ask spreads in the foreign exchange hedging market

	GBP/USD			EUR/USD			JPY/USD		
	2-year	5-year	10-year	2-year	5-year	10-year	2-year	5-year	10-year
Mean	3.83	3.19	2.91	3.75	2.88	3.03	4.28	4.19	3.76
Median	4.00	3.00	2.90	4.00	3.00	3.82	4.00	4.00	3.00
Max.	12.00	8.10	10.90	6.20	6.00	6.45	10.00	8.25	10.00
Obs.	2062	2062	2061	2062	2062	2061	2062	2062	2061

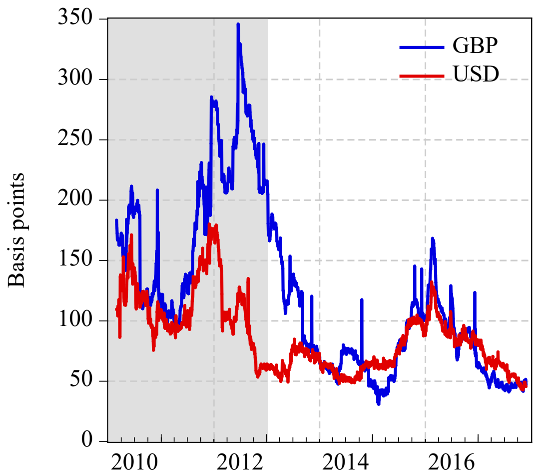
Note: The table shows the bid/ask spreads from 2010-2017 in the foreign exchange hedging market across different currency pairs and maturities. The data is extracted from cross currency basis swaps quoted on Bloomberg. All numbers are in basis points.

Figure OA.1
Libor and CP rates

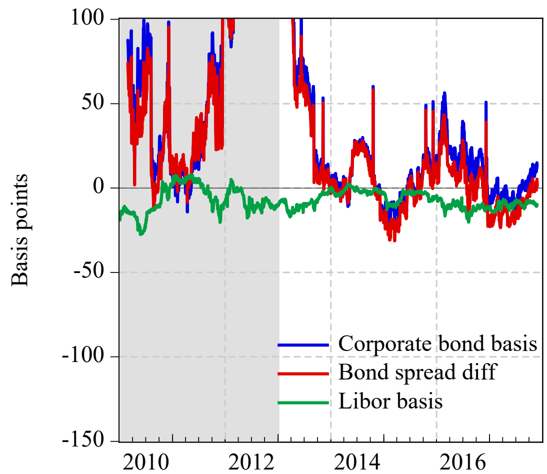


Note: The panels show 3-month A-1/P-1 commercial paper rates and the 3-month Libor rates in GBP, JPY and USD. In EUR I use Euribor as this is the most commonly used benchmark rate and the underlying benchmark rate in euro area Libor swaps. The Commercial Paper rates are quoted rates from Tradeweb and sourced through Thomson Reuters Eikon. The Libor and Euribor rates are downloaded from Bloomberg.

Figure OA.2
Bond spreads and the Libor basis, 5-year maturity



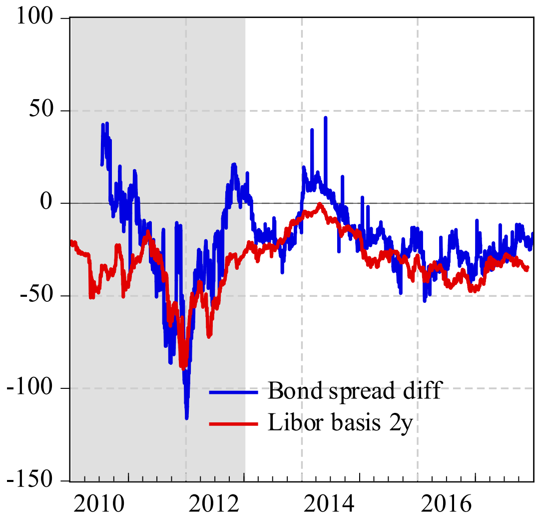
(a) Bond spreads in GBP and USD



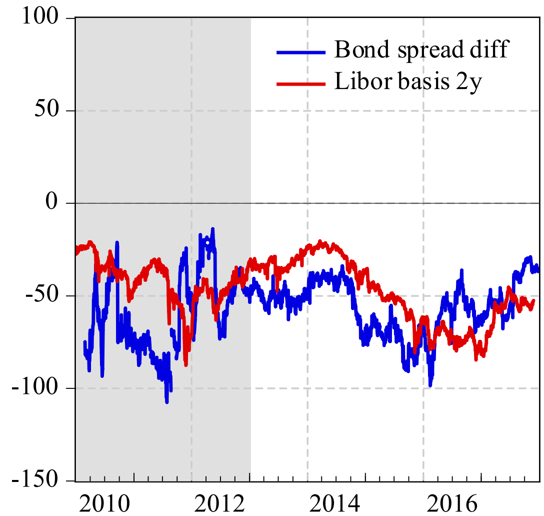
(b) Corporate bond basis GBP/USD

Note: The left-hand graph shows the corporate bond spread for a basket of corporate issuers with the same rating and domiciled in the same country in GBP and USD. The right hand graph shows i) the corporate bond spread differential (GBP minus USD) based on the corporate bond spreads depicted in graph a, ii) the Libor basis which is the difference between the synthetic and direct Libor swap rate, and iii) the corporate bond basis for similar issuers which is the difference between synthetic and direct corporate bond rate. Negative values of the basis mean that the direct corporate bond rate in USD is lower than the synthetic corporate bond rate implied from foreign currency denominated bonds. The corporate bond basis is zero if the Libor basis and the bond spread differential are equal. The shaded area illustrates the European sovereign debt crisis from 2010 to 2012.

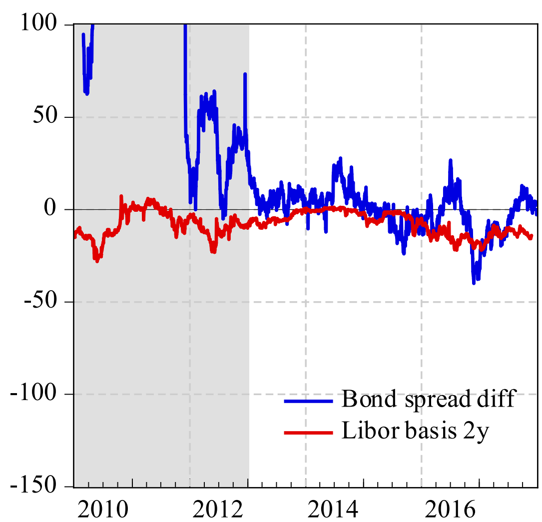
Figure OA.3
Bond spreads and the Libor basis - 2 year



(a) EUR



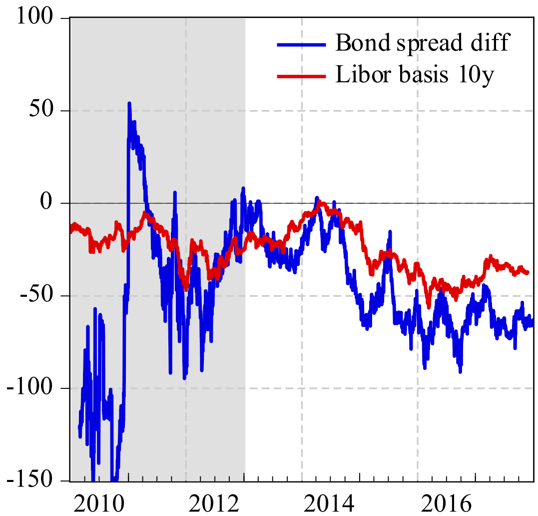
(b) JPY



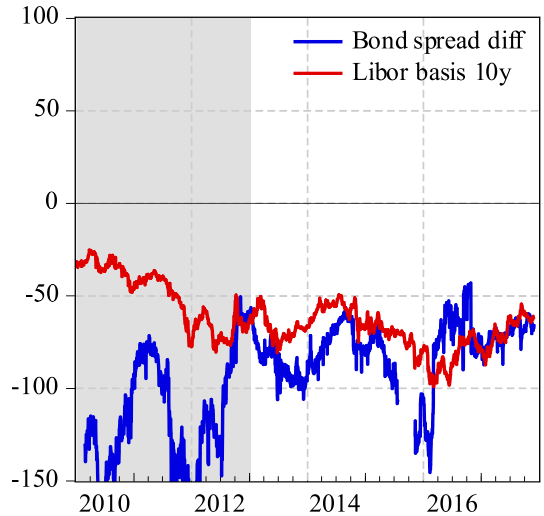
(c) GBP

Note: The graph shows the 2-year Libor basis and the corresponding corporate bond spread differential for high quality (AA) bonds denominated in EUR, JPY and GBP versus USD. The Corporate bond basis is zero if the Libor basis and the bond spread differential are equal.

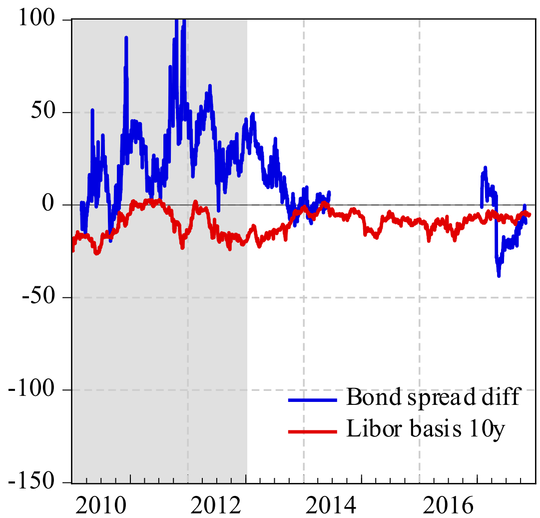
Figure OA.4
Bond spreads and the Libor basis - 10 year



(a) EUR



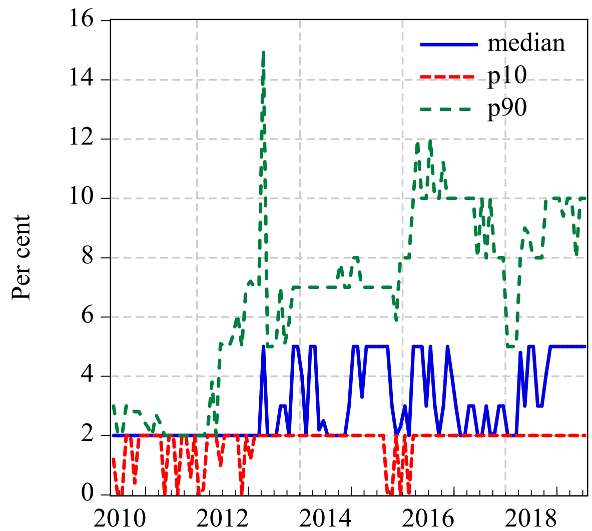
(b) JPY



(c) GBP

Note: The graph shows the 10-year Libor basis and the corresponding corporate bond spread differential for high quality (AA) bonds denominated in EUR, JPY and GBP versus USD. The Corporate bond basis is zero if the Libor basis and the bond spread differential are equal.

Figure OA.5
Haircut levels from NY Fed



Note: The figure depicts the evolution of the median, the 90th percentile and the 10th percentile of haircut levels for international securities in the U.S. tri-party repo market and Fixed Income Clearing Corporation (FICC).

Chapter 5

Life After Libor*

*This article is forthcoming in Journal of Financial Economics

5.1 Introduction

The London Interbank Offered Rate (Libor) is arguably the financial world's most important number; it is a proxy for banks' marginal funding costs and serves as benchmark rate in trillions of loans, floating-rate debt, and financial contracts. The Libor manipulation scandal and a shrinking interbank debt market caused a push toward alternative benchmark rates, culminating in the "Libor funeral" – a speech by Bailey (2017) announcing that the publication of Libor cannot be guaranteed beyond 2021. The Libor funeral caused a transition toward transaction-based overnight rates, which will serve as alternative benchmark rates. In theory, overnight rates are virtually risk-free and simply reflect the current level of policy rates. In practice however, the alternative benchmark rates are prone to upward or downward spikes (depending on the region) at regulatory reporting dates, can differ substantially from other overnight rates in the same region, and occasionally exhibit large volatility.[1]

Why are some benchmark rates prone to upward spikes while others are prone to downward spikes? What drives movements in the alternative benchmark rates? What are the implications of the high volatility for term rates? To address these questions, we first describe the alternative benchmarks and the institutional setting. Afterwards, we derive and test three hypotheses about the alternative benchmark rates. Finally, we examine the consequences of the funeral for term rates and discuss its broader implications.

Focusing on the alternative benchmark rates in the U.S., the U.K. and the Eurozone (henceforth, Europe), we start by illustrating the difference between the alternative benchmark rates and or, in Europe, its European counterpart Euribor. Panel (a) of Figure 5.1 shows whisker plots of the spread between alternative benchmark rate and overnight in the three regions, illustrating large cross-country differences. While the spreads are stable around zero in the U.K., they are on average −8.5 basis points in Europe with occasional downward spikes and fluctuate between −15 and 15 basis points in the U.S. In interpreting these spreads, it is important to note that all rates are overnight lending rates for low-risk borrowers and should therefore be close to the "risk-free" rate. More importantly, given that the alternative rates are intended to replace Libor as benchmark rate, spread changes of a few basis points can translate to valuation changes of millions of dollars, making a deeper understanding of the drivers behind these alternative benchmarks crucial.

To develop this understanding, we first note that all three alternative benchmark rates are transaction-based and that the transactions underlying these rates can either be collateralized or uncollateralized. Moreover, the underlying transactions can comprise up to three different types – non-bank to bank lending (*T1*), bank to bank lending (*T2*), and bank to non-bank lending (*T3*). In the U.S., the alternative benchmark rate is Sofr (the Secured Overnight Financing Rate), which comprises *collateralized* transactions of all three types (using U.S. Treasuries as collateral). In the U.K. and Europe, the alternative benchmarks are Sonia (the Sterling Overnight Index Average) and

[1] The most dramatic example of such volatility was the "repo squeeze" in mid-September 2019, when the alternative benchmark rate for the U.S. unexpectedly spiked more than 150 basis points.

ESTR (the Euro Short Term Rate), respectively. Both rates are *uncollateralized* and only comprise transactions where banks borrow from either non-banks or other banks, that is, transaction of type *T1* and *T2*.

As a next step, we link the behavior of the alternative benchmarks to financial regulation and monetary policy, deriving three testable hypotheses. First, whether a rate is prone to upward or downward spikes depends on the types of transactions underlying the rate, the lenders' financial constraints, and the availability of alternative cash placements. If banks have ample amounts of reserves, tighter regulatory constraints lower their demand for borrowing money and therefore lower interest rates. This is the case in the U.K. and Europe, where banks have large amounts of reserves and the alternative benchmarks only comprise bank borrowing transactions. By contrast, rates increase with tighter regulatory constraints if banks are in need for cash and reluctant to lend money. This is the case in the U.S., where reserves are concentrated within few large banks and the alternative benchmark also reflects bank to non-bank transactions. Second, an increase in government debt increases the alternative benchmarks. This increase is due to a "crowding out" effect, where investors prefer Treasury debt instead of lending money to banks. In addition, the impact of more government debt is amplified for SOFR because an increase in government debt leads to more demand for collateralized borrowing, which directly affects collateralized rates. Third, if banks do not have ample reserves, a drop in central bank reserves increases banks' demand for borrowing and therefore increase interest rates.

To test our first hypothesis, we use regression analysis to examine spikes in the alternative benchmarks at regulatory reporting dates. On average, SOFR is 20.25 basis points higher at quarter-ends compared to other dates. By contrast, both SONIA and ESTR are significantly lower at quarter-ends compared to other dates. However, in comparison to SOFR, the magnitude of these spikes – on average -2.12 basis points for SONIA and -0.51 basis points for ESTR – is several orders of magnitude smaller.

Turning to our second and third hypothesis, we examine the link between daily or weekly changes in the alternative benchmarks and the quantities of government debt and bank reserves. In addition, we investigate how changes in transaction volumes affect the alternative benchmarks. For the U.S., we find a strong positive link between the amount of Treasuries outstanding and SOFR. In addition, more SOFR transactions increase the rate and a higher amount of bank reserves tends to coincide with drops in SOFR (although the relationship is insignificant in this test). In the U.K., a higher amount of gilts outstanding significantly increases SONIA and more excess reserves in Europe correspond to a (borderline insignificant) drop in ESTR. In both the U.K. and Europe, more transactions increase the alternative benchmarks. Contrasting the results for the U.K. and Europe with the U.S. shows that SOFR is more affected by these micro structure effects; especially fluctuations in the quantity of government debt have a stronger impact on SOFR compared to SONIA and ESTR.

Motivated by these findings and by our hypotheses, we examine changes in SOFR more closely. We construct a proxy of the fraction of non-bank to bank lending in SOFR and find that this proxy together with the amount of government debt outstanding explains 13% of the daily variation in SOFR on non-reporting dates. In addition, the impact of changes in reserves on SOFR strengthens between mid-2018 and late 2019, when reserves in the U.S. became less abundant and more primary dealer repos increase SOFR.

To provide a closer link between the reporting date spikes in SOFR, or, more broadly, U.S. repo rates, and regulatory constraints we perform two simple difference-in-difference analyses. First, investigating the 2010 – 2019 period, we show that quarter-end spikes in U.S. repo rates appeared only after January 2013, the date at which financial institutions started reporting their leverage ratios (LRs) to regulators. Second, we examine the difference between banks' repo borrowing on quarter-ends and their quarterly average repo borrowing. We split the sample between U.S. banks, who report quarterly averages of their leverage ratios and hence have no incentive to reduce their positions at quarter-ends, and foreign banking offices (FBOs), who report quarter-end snapshots of their leverage ratios. We find that FBOs significantly decrease their repo borrowing at quarter-ends after 2013 compared to U.S. banks.

Turning to the implications of the funeral for term rates, Panel (b) of Figure 5.1 shows the spreads between 3-month averages of the alternative reference rates computed "in arrears" (averaging over the following 90 business days) and 3-month LIBOR rates. The figure shows that term rates based on the alternative benchmarks are substantially lower than term LIBOR rates and we show that a large part of this difference is due to the term and credit premiums embedded in .

We next examine how the funeral affected the open interest in Euro-dollar futures (contracts referencing). While the open interest for GBP contracts decreased, neither USD nor EURIBOR futures were affected. These steady volume in Euro-dollar futures suggest a slow transition away from and pose practical challenges because futures expiring after December 2021 will potentially lack an underlying reference rate.

Finally, we construct SOFR term rates based on futures contracts and highlight two properties of term SOFR. First, SOFR decreased during the March 2020 market turmoil when LIBOR rates are soaring. This observation resonates with Schrimpf and Sushko (2019), who survey the alternative benchmarks and emphasize that, during crisis periods, SOFR can be substantially below financial intermediaries' marginal funding costs. Second, the 1-month term rates based on SOFR futures also exhibit predictable upward spikes on regulatory reporting dates with term rates being on average 0.77 basis points higher in the last month of a quarter.

Our findings shed more light on the drivers of overnight rates and contribute to a large literature examining the working of the Fed funds market (Furfine, 1999, Ashcraft and Duffie, 2007, Afonso and Lagos, 2015), the different segments of the U.S. repo market (Bartolini et al., 2010, Gorton and Metrick, 2012, Krishnamurthy et al., 2014, Copeland et al., 2014, Munyan (2017) among many others), European money markets (Mancini et al., 2015, Nyborg, 2019), money markets in the U.K. (Bicu et al., 2017) and the impact of post-crisis regulation on these markets (Banegas and Tase, 2017, Duffie, 2017b, Munyan, 2017, Ranaldo et al., 2020 among others). Specifically, we show that the composition of the marginal lenders, the Treasury debt outstanding, and the amount of excess reserves are key drivers in the alternative benchmark rates and most pronounced for the U.S.

5.2 Background and Hypothesis Development

To understand the main drivers of the alternative benchmark rates and why they are prone to either upward or downward spikes, we give an overview of their main features and provide a detailed background on the different types of transactions that can be part of these alternative rates. Afterwards, we discuss the impact of regulatory constraints on the different transactions and derive three testable hypotheses about the behavior of the alternative benchmarks.

5.2.1 The Alternative Reference Rates

The alternative benchmark rates in the U.S., the U.K., and Europe are all transaction-based overnight rates. In the U.S., the underlying transactions are collateralized (with U.S. Treasuries) while they are uncollateralized in the U.K. and Europe. Moreover, the underlying transactions can be grouped into three different types – non-bank to bank lending (*T1*), bank to bank lending (*T2*), and bank to non-bank lending (*T3*) – which we illustrate in Figure 5.2. In transactions of type *T1*, the non-bank lenders are typically cash-rich companies or money market mutual funds (MMFs), who place part of their cash holdings in overnight transactions with banks. Banks use these overnight loans to fund their own positions or act as intermediaries, channeling the funds either to other banks (transactions of type *T2*) or to non-bank cash takers like hedge funds and investment managers (transactions of type *T3*).

In contrast to the alternative benchmarks, LIBOR is an interbank rate that should reflect the interbank rate at which one prime bank could borrow money from another prime bank. Traditionally, this rate is based on "expert judgments" by each panel bank, but the manipulation scandal led to a reform (see Wheatley, 2012), pushing panel banks to replace these "expert judgments" with market-based rates (such as commercial paper rates), where possible. As a result, the Intercontinental Exchange (ICE) took over the publication of in 2014 and announced the transition toward the reformed methodology in April 2018 (see ICE, 2018). Hence, rates can be thought of as hypothetical interbank transactions of type *T2* and, more recently, as non-bank to bank transactions of type *T1* because non-banks are the main commercial paper investors. Similarly, EURIBOR was largely based on "expert judgements" and recently reformed by the European Money Market Institute (EMMI) to reflect actual transactions where possible. In contrast to , there is no overnight EURIBOR rate and we therefore compare ESTR to EONIA (the European Overnight Index Average), which, according to the EMMI, can be considered as the 1 day EURIBOR rate.[4]

[4] EONIA is based on interbank transactions executed by a similar panel of banks as EURIBOR. The key difference between EONIA and overnight in the U.S. and the U.K. is that EONIA is fully transaction-based.

To examine fluctuations in the different rates that are not simply driven by changes in policy targets, we focus on the spreads between overnight rates and key policy rates that reflect the level of the target interest rate in each respective area. For the U.S., we use the "Interest On Excess Reserves" (IOER) that banks receive for placing their excess reserves with the Federal Reserve Bank (Fed). As key policy rate for the U.K., we use the "bank rate", which is the rate at which banks' central bank reserves are remunerated at the Bank of England (BoE). For Europe, we use the "deposit rate" that banks receive for placing their central bank reserves with the European central bank (ECB). Because all three policy rates are constant unless central banks change their policy targets, the resulting spreads reflect any rate moves that are unrelated to policy rate changes. The blue lines in Figure 5.3 show the alternative benchmarks relative to the policy rates and the black lines show overnight rates for the U.S. and the U.K. or Eonia rates for Europe, all relative to respective policy rates. As we can see from the figure, the alternative benchmarks exhibit large volatility at quarter-end dates (as illustrated by the gray vertical lines) and the U.K. overnight rate shows a visible decline in mid-2018, which, as we explain in more detail below, can be attributed to the reform.

The Secured Overnight Financing Rate (SOFR)

Sofr is the proposed U.S. Libor replacement, suggested by the alternative reference rates committee (ARRC). It is based on collateralized overnight transactions (repos) with U.S. Treasuries as collateral and comprises three types of transactions. First, broad repos (similar to *T1*), also called tri-party repos (because they are cleared through a third party which is either Bank of New York or JP Morgan), in which the typical lenders are MMFs and other non-banks. Second, inter-dealer repos (similar to *T2*), which are called General Collateral Financing (GCF) repos. Third, bilateral repo transactions, which are typically between dealers and non-banks (similar to *T3*). Figure 5.4 shows that bilateral and tri-party repos (type *T3* and *T1*) dominate Sofr while GCF repo comprise a small share of the volume.

To understand the potential impact of the different types of transactions on Sofr, we first note that interest rates in the bilateral segment can be driven by the lender's demand for borrowing a specific security instead of borrower's demand for cash (see, for example, Duffie, 1996). However, the calculation methodology in Sofr accounts for this by removing the bottom 25th percentile of the rate distribution within this segment. In addition, transactions of types *T2* and *T3* in Sofr are largely driven by demand for cash because central bank reserves in the U.S. are concentrated within the largest banks and small banks or non-banks are unable to borrow directly in transactions of type *T1*. Moreover, a key difference between the U.S. and other jurisdictions is that the Fed's reverse repo facility (introduced in September 2014) allows MMFs and other investors to engage in overnight repo transactions with the Fed at a pre-specified rate. This reverse repo facility effectively puts a lower bound on repo rates because lenders with access to the facility have no incentive to lend at a rate below the Fed's reverse repo rate.

As illustrated in Panel A of Figure 5.3, SOFR is significantly more volatile than the overnight rate and exhibits large upward spikes that frequently occur at quarter-end dates. Note that the y-axis in Panel A is truncated at 100 basis points, which SOFR exceeded in September 2019. By comparison, the overnight rate is stable with no visible upward or downward spikes.

The Sterling Overnight Index Average (SONIA)

SONIA captures overnight funding costs in sterling and is a wholesale funding rate which comprises both non-bank to bank and bank to bank lending (transactions of type *T1* and *T2*). SONIA already serves as benchmark rate in overnight index swaps (OIS) and was reformed in April 2018, including an even broader set of wholesale transactions (more transactions of type *T1*) and adjusting the averaging methodology.[6] This reformed SONIA rate is the proposed LIBOR replacement in the U.K.

Panel B of Figure 5.3 compares SONIA and the U.K. rate. The blue line in Figure 5.3 shows the reformed SONIA rate, which the BoE calculates from 2016 on. As we can see from the graph, SONIA tends to spike downward on reporting dates and these spikes have somewhat diminished since mid-2018. By contrast, the overnight rate does not exhibit any regular upward or downward spikes. However, the implementation of the new waterfall methodology in 2018 lead to a drop in overnight from approximately −3 basis points in Q2 2018 to −7 basis points in Q4 2018. When comparing SONIA to the rates in the U.S., it is important to note the different scaling of the y-axis in Panel B, which ranges from −10 basis points to 5 basis points, suggesting that SONIA is significantly less volatile than SOFR.

The Euro Short-Term Rate (ESTR)

ESTR is an uncollateralized overnight rate that comprises non-bank to bank and bank to bank lending (transactions of type *T1* and *T2*) and the proposed replacement for the Euro area. This rate is officially published from October 2019 on and a pre-ESTR version is available from 2016 on.

Instead of , the benchmark rate for the Euro-area is EURIBOR (the European interbank offered rate) and because overnight EURIBOR does not exist, we compare ESTR to EONIA (the European Overnight Index Average), which is an average of overnight interbank transactions (of type *T2*), executed by 28 panel banks. According to the benchmark provider, EONIA can be considered as the 1 day EURIBOR rate and also serves as the current benchmark in euro-denominated overnight index swaps. While the transactions underlying ESTR are reported by a similar panel of banks as in EONIA, the ESTR transaction volume is on average ten times larger than the EONIA volume, suggesting that the majority of ESTR transactions are of type *T1*.

[6] As explained by the BoE, "the coverage of SONIA [is] being broadened to include overnight unsecured transactions negotiated bilaterally as well as those arranged via brokers [...]" (see `https://www.bankofengland.co.uk/-/media/boe/files/markets/benchmarks/sonia-as-the-risk-free-reference-rate-and-approaches-to-adoption.pdf?la=en&hash=35A8953638C9101CAB7204688918D501DA04D7C0`)

Panel C of Figure 5.3 compares ESTR and to EONIA. As we can see from the figure, ESTR is significantly lower than EONIA and exhibits small downward spikes at quarter-ends and irregular upward spikes. The large difference between EONIA and ESTR can be explained by the fact that a large part of the lending in ESTR comes from non-banks (transaction type *T1*) which do not have access to the ECB deposit facility and therefore accept rates below the deposit rate.[7]

5.2.2 The Impact of Regulatory Constraints

We distinguish two types of regulatory constraints that affect the interest rates in the three transactions shown in Figure 5.2.[8] First, risk-weighted capital requirements (based on Value-at-Risk type constraints), which lower banks' incentives to lend money uncollateralized because uncollateralized lending increases the risk-weighted assets. Second, the leverage ratio (LR), which is defined as:

$$\text{LR} = \frac{\textsc{Tier 1 Capital}}{\textsc{Total Exposure}}, \tag{5.1}$$

where TOTAL EXPOSURE comprises on-balance-sheet assets, securities-financing transactions (SFTs) such as repos and security lending, and off-balance sheet items (e.g. derivatives). Because the computation of TOTAL EXPOSURE does not take netting into account, borrowing money increases the TOTAL EXPOSURE, irrespective of whether the borrowed money is invested in safe or risky assets. Hence, the LR lowers banks' incentives to borrow money and gives banks an incentive to reduce their repo intermediation (i.e. borrowing from one party to lending to another; see Duffie, 2017b).

The LR was introduced after the financial crisis, banks started reporting their LRs to regulators in January 2013, and public disclosure of the LR was introduced in January 2015. The way TOTAL EXPOSURE is reported varies across countries. In the U.S., banks report quarterly averages based on daily data for on-balance-sheet items, but quarterly averages based on *month-end snapshots* for SFTs and off-balance-sheet items. In the U.K., banks reported TOTAL EXPOSURE based on quarterly averages of month-end snapshots until December 2017 and now report quarterly averages based on daily observations.[9] Banks in Europe report their LR using quarter-end snapshots. The use of month-end or quarter-end snapshots for LR reporting implies tighter regulatory constraints at month-ends or quarter-ends and allows us to test the impact of regulatory constraints on the alternative benchmarks.

We now discuss the impact of regulatory constraints on borrowing and lending in transactions

[7] The ECB explains on its website that ESTR reflects banks borrowing from other banks as well as other counterparties, such as money market funds, insurance companies and other financial corporations (see `https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/euro_short-term_rate/html/eurostr_qa.en.html`). Hence, most transactions in ESTR can be thought of as *T1*.

[8] We simplify our examination of the regulatory background by not discussing the Liquidity Coverage Ratio (LCR) because this regulation mainly affects term rates with longer maturities.

[9] The concern that month-end snapshots could lead to window-dressing lead the BoE to change the reporting requirement (see Jones (2016)).

T1-*T3*. First, lending from non-banks to banks (*T1*) increases banks' liabilities, independent of whether the transaction is uncollateralized or collateralized. Hence, all else equal, a more binding leverage ratio makes banks reluctant to borrow and lowers the interest rate banks are willing to pay non-banks.

Second, in interbank transactions (*T2*), tighter regulatory constraints can lower both the borrowers' supply and the lenders' demand for cash. Because uncollateralized transactions increase the lenders' risk-weighted assets, tighter constraints reduce the supply in *T2* transactions. Moreover, because the borrower in *T2* is another bank and all borrowing affects the LR, tighter regulatory constraints can lower demand in *T2* transactions. However, this is only the case if liquidity in the interbank market is abundant and banks have little incentive to borrow cash. If liquidity is unevenly distributed – e.g. because some banks do not have access to non-bank funding – tighter regulatory constraints leave the borrowing demand in *T2* transactions largely unaffected. In this situation, banks in need of liquidity push collateralized interbank rates up because tighter regulatory constraints give lenders less incentives to perform repo intermediation. This effect is particularly strong if the interest rates on lending from non-banks to banks (*T1*) are floored by central bank facilities that open up for non-banks to place money directly in the central bank.

Finally, for lending from banks to non-banks (*T3*), the borrowers' demand for cash is unaffected by regulatory constraints while the lenders' supply of cash decreases. For uncollateralized transactions, supply decreases because uncollateralized lending increases banks' risk-weighted assets. Collateralized transactions are impacted indirectly because a tighter LR constraint lowers banks' incentives for repo intermediation. Hence, tighter regulatory constraints tend to increase rates in transactions of type *T3*.

5.2.3 The Impact of Government Debt and Excess Reserves

We next discuss the impact of government debt and excess reserves on overnight rates. Figure 5.2 suggests that Treasuries offer an alternative way of placing cash for non-bank lenders. Because government debt issued by developed countries is arguably the safest and most liquid investment, lenders tend to prefer investing in Treasuries and a higher Treasury supply lowers the lending supply.[11] Hence, more Treasury supply has a "crowding out" effect that increases interest rates in transactions of type *T1*. In addition, more Treasury supply directly impacts collateralized rates because levered Treasury investors need to finance a larger quantity of positions. This increased financing need increases the demand for repo borrowing and collateralized rates in *T1*–*T3*.

Another asset on banks' balance sheets illustrated in Figure 5.2 are central bank reserves. If a bank has more central bank reserves, it has more cash available for investments and a lower demand for borrowing. Hence, more central bank reserves lower banks' demand for borrowing, which can

[11] This argument rests on the Treasury department placing the proceeds on its account in the central bank, thereby temporarily reducing the money supply. After the financial crisis, it is common practice for Treasury departments in the U.S., the U.K, and several European countries to place their proceeds in the central bank.

lower interest rates in transactions of type *T1*. However, if reserves are ample, a small change in reserves is less likely affect banks' demand for cash (see Afonso et al., 2020). While the amount of central bank reserves increased sharply after the financial crisis, it is worth noting that reserves in the U.S. are concentrated within few large banks (see Cœuré). This reserve concentration leads to more demand for cash by banks and hence, tighter regulatory constraints increase interbank rates in the U.S.

5.2.4 Testable Hypotheses

Panel A of Table 5.5 summarizes the background behind the three alternative benchmarks. While the marginal lenders in SOFR can be banks or non-banks, most lending in SONIA and ESTR is done by non-banks. In addition, SOFR is different from the other two rates because non-bank lenders in SOFR can alternatively place their money at the Fed's reverse repo facility (which serves as a floor for the rates), because SOFR also includes transactions of type *T3*, and because SOFR is collateralized. By contrast non-banks in the U.K. and Europe do not have access to a deposit facility, both SONIA and ESTR are uncollateralized and only include transactions of type *T1* and *T2*.

To derive our hypotheses, we build on theories of segmented markets in which an unconstrained non-bank interacts with a constrained bank intermediary (see, for example, He and Krishnamurthy, 2012 or Gârleanu and Pedersen, 2011). In these theories, a more binding capital constraint reduces the bank's ability to borrow money from the non-bank. Hence, in equilibrium, non-bank to bank lending rates decrease to induce the non-bank to lend less. At the same time, a more binding capital constraint lowers the bank's ability to lend money to other banks, thereby increasing interbank rates. In the appendix, we illustrate this mechanism in a simple model where the bank faces a LR constraint.

Applying this logic to our context, recall that non-bank lenders in the U.S. have access to the Fed's reverse repo facility while non-bank lenders in the U.K. and Europe cannot place cash with their central banks. Hence, tighter regulatory constraints lower the rates in transactions of type *T1* for SONIA and ESTR but not for SOFR. In addition, small banks and non-banks in the U.S are usually unable to borrow directly from MMFs but rely on repo intermediation from large banks. Moreover, according to CGFS (2017), European banks are an important counterparty in U.S. repo markets, suggesting that their regulatory quarter-end constraints impact U.S. repo rates. Taken together, for SOFR, tighter regulatory constraints increase the rates in transactions of type *T2* or *T3*, and we hypothesize that tighter regulatory constraints lead to large increases in SOFR. For SONIA and ESTR, the rates in transactions of type *T2* likely increase with tighter regulatory constraints, but because transactions of type *T1* make up the majority of the volumes, we expect that tighter regulatory constraints decrease SONIA and ESTR.

Tighter regulatory constraints correspond to large increases in SOFR and moderate decreases in SONIA and ESTR.

Next, because SOFR is a collateralized rate, increases in Treasury supply increase the demand for repo financing and therefore have a direct impact, increasing the repo rate. In addition, as discussed in Section 5.3.2, an increase in the supply of safe assets increases rates in *T1* transactions because non-bank lenders can invest more in Treasuries. Hence, we hypothesize that an increase in Treasury debt outstanding increases interest rates for all alternative benchmarks but has a stronger effect on the collateralized rate SOFR.

An increase in Treasury debt outstanding increases all three alternative benchmark rates and has the largest impact on SOFR.

Finally, building on our discussion in Section 5.3.2, we argue that more central bank reserves lower banks' demand for overnight borrowing, which lowers interest rates. However, the impact of changing reserves diminishes when banks have ample reserves and their demand for liquidity is saturated.

If banks are not saturated with central bank reserves, a decrease in the amount of central bank reserves increases the alternative benchmark rates.

Panel B of Table 5.5 summarizes our three hypotheses and shows how tighter regulatory constraints, more Treasury debt outstanding, and more central bank reserves affect SOFR, SONIA, and ESTR.

5.3 Drivers of the Alternative Benchmark Rates

In this section, we examine how regulatory reporting dates, government debt, and excess reserves affect the alternative benchmark rates. We test our three hypotheses for the alternative benchmarks in the U.S., the U.K., and Europe and conduct additional tests for the alternative benchmark in the U.S., where we expect the largest effects.

5.3.1 Reporting Date Spikes

We test Hypothesis 5.2.4 by comparing the average of the alternative benchmarks to their value at quarter-ends, year-ends, and month-ends, using regression analysis. We focus on three dummy variables, QEnd, YEnd, and MEnd $\setminus$ QEnd, which are equal to one if the observation is from the last trading day of the quarter, the last trading day of the year, or the last trading day of the month but not quarter-end, respectively. As in Figure 5.3 before, we use the full period for which the alternative benchmarks are available and focus on their spread over the key policy rate, which captures rate moves unrelated to changes in key policy rates.

Panel (1) of Table 5.2 shows that SOFR is on average 20.25 basis points higher at quarter ends and 10.06 basis points higher at month-ends, compared to its time series average. Panel (2) repeats the analysis with year-quarter fixed effects. Adding year-quarter fixed effects reduces the potential impact of a time trend and ensures that QEnd reflects the difference between the quarterly average and the quarter-end value of SOFR. As we can see from Panel (2), adding year-quarter fixed effects leaves the coefficients virtually unchanged. Focusing next on reformed SONIA, Panel (3) of Table 5.2 shows significant average downward spikes of -2.12 basis points at quarter-end dates and less-significant average downward spikes of -0.38 basis points at other month-end dates. Panel (4) confirms the robustness of this finding to controlling for year-quarter fixed effects. Turning to ESTR, Panel (5) shows small downward spikes of -0.51 basis points at quarter-ends, which are more pronounced at year-ends, and Panel (6) confirms that these spikes are robust to controlling for year-quarter fixed effects. In contrast to SOFR and SONIA, ESTR does not exhibit any significant month-end spikes.

Taken together, Table 5.2 documents a qualitative difference between SOFR (which is prone to upward spikes) and SONIA or ESTR (which are prone to downward spikes), as well as a quantitative difference – spikes in SOFR are several orders of magnitude larger than the spikes in SONIA or ESTR. In line with Hypothesis 5.2.4, the large upward spikes in SOFR reflect borrowers' cash demand in transactions *T2* and *T3*, as well as the floor introduced by the reverse repo facility for *T1* transactions. By contrast, the downward spikes in SONIA and ESTR reflect the absence of a floor for transactions of type *T1* and the fact that these rates mainly comprise transactions of type *T1*. In addition, the significant month-end spikes in SOFR and SONIA are in line with regulatory reporting based on month-end snapshots in the U.S. and the U.K. while the absence of month-end spikes in ESTR reflects the quarter-end reporting in Europe.

5.3.2 The Impact of Government Debt and Excess Reserves

We next examine the main drivers of the alternative benchmarks aside from regulatory reporting dates. To that end, we remove all month-end observations from the data and examine daily or weekly changes in the alternative benchmarks relative to the key policy rates in the respective area.[13]

We construct two variables that are available on a daily basis – the amount of government debt outstanding and the transaction volume underlying the alternative benchmarks. First, to obtain the quantity of government debt outstanding, we collect auction data for U.S. Treasuries, U.K. gilts, and German Treasuries. We then use the issuance volumes, auction dates, and maturity dates to construct daily volumes of U.S. and U.K government debt outstanding and to approximate the volume of safe assets in the Euro-area. Second, because a more detailed breakdown into transaction types is only available for SOFR, we simply use the total transaction volumes underlying the alternative benchmark rates in this section and conduct additional tests for SOFR later. In interpreting the role of transaction volumes, it is important to note that SONIA and ESTR volumes are largely transactions of type *T1*, while changes in bilateral repo volumes are the main driver of daily fluctuations in SOFR volumes. Hence, higher SONIA or ESTR volumes reflect banks' demand for funds from non-banks, which increases the rate. Similarly, a higher SOFR volume reflects stronger demand for

[13] Because the goal of these tests is to examine the link between SOFR and other variables under "normal" market conditions, we also remove the week from September 16 – September 20, 2019, when SOFR spiked up to 5.23% to avoid our results being driven by large outliers in the data.

funds from non-banks in the bilateral repo, also increasing the rate.

In addition, we use a weekly measure of bank reserves in the U.S., the U.K. and Europe and also reexamine the impact of government debt and transaction sizes on a weekly frequency.

Confirming Hypothesis 5.2.4, Panel (1) of Table 5.3 shows that an increase in Treasury debt outstanding corresponds to large, statistically significant increases in SOFR. This impact remains statistically significant in Panel (2), where we examine weekly changes instead of daily changes and control for changes in reserves. In addition, more underlying transactions increase SOFR and, together with changes in government debt outstanding, the two variables explain 12% of the daily variation in SOFR. Focusing next on the U.K., Panel (3) of Table 5.3 shows that an increase in gilts outstanding increases reformed SONIA while daily changes in transaction volumes have an insignificant impact. For weekly instead of daily changes, Panel (4) shows that gilts outstanding become insignificant while increases in transaction volumes correspond to significant increases in reformed SONIA (although only at a 10% significance level). Examining ESTR, Panels (5) and (6) show an insignificant impact of changes in the amount of German Treasuries outstanding, while fluctuations in transaction volumes have a positive and significant impact in both specifications. Taken together, Table 5.3 confirms Hypothesis 5.2.4, which suggests that the impact of government debt is strongest for the U.S. because SOFR is collateralized with Treasury debt and therefore changes in the volume of debt outstanding have a direct impact on SOFR.

Turning to Hypothesis 5.2.4, we find that both SOFR and SONIA are largely unaffected by changes in reserves while we find a borderline insignificant impact for ESTR.[15] The insignificant impact of reserves on the alternative benchmarks can reflect the fact that banks had ample reserves for most of the sample; only U.S. banks struggled with less ample reserves from mid-2018 and we re-examine the impact of reserves for this period in the following section.

5.3.3 Additional Evidence from the U.S.

Because the results so far suggest that SOFR is most affected by the market idiosyncracies described in Section 5.2, we next utilize the more granular U.S. data to conduct additional tests of our hypotheses for SOFR.

First, instead of using daily changes in total SOFR volumes, we construct the share of tri-party repos underlying SOFR. An increase in this share corresponds to more transactions of type *T1* in SOFR, which lowers the rate because rates in which non-banks act as lenders are usually lower than rates in which banks act as marginal lenders. In line with this assertion, Panel (1) shows a strong negative link between SOFR and the tri-party share in SOFR while the impact of changes in Treasury debt outstanding remains virtually unchanged. While the link between tri-party share and SOFR is arguably mechanical (tri-party repo rates are typically below GCF and bilateral rates), it highlights that movements in SOFR can be due to compositional changes in the repo market that are

[15] Despite being borderline insignificant for ESTR, controlling for changes in reserves increases the daily R^2 of 6% to a weekly R^2 of 22%, suggesting that fluctuations in reserves help explaining fluctuations in ESTR.

unrelated to banks' funding costs – for example, unusually low bilateral transaction volumes (e.g. because hedge funds scale down their leverage) combined with unchanged tri-party volumes lower SOFR without having an obvious impact on banks' funding costs.

Next, we focus on weekly changes and add the total amount of bank reserves as explanatory variable. In addition, we obtain data on overnight Treasury repos and reverse repos by primary dealers. Primary dealers are net repo borrowers since 2013, which allows us to use log-changes for our analysis. We expect that more primary dealer net repo borrowing increase SOFR because it reflects an elevated demand for repo funding from the financial sector. In line with these arguments, Panel (2) of Table 5.4 shows that all explanatory variables have the expected signs – a higher amount of reserves lowers SOFR while more primary dealer net repos increase SOFR.

We next test if the link between SOFR and reserves is stronger when the aggregate level of reserves is relatively low. To that end, we interact changes in reserves with a dummy variable that equals one from mid-2018 on (when reserves reached a low level) and zero otherwise. Panel (3) of Table 5.4 shows that the impact of reserves is over 10 times stronger and statistically significant ($t = -2.64$) when interacted with the mid-2018 dummy variable.

Finally, we address a potential shortcoming of our analysis. Due to central bank purchases, the amount of Treasury debt can differ from the publicly-available debt level. In particular, an increase in reserves can decrease the amount of publicly-available debt and therefore affect SOFR through a change in the supply of safe assets. To address this concern, we construct a measure of publicly-available Treasury debt outstanding by subtracting Fed Treasury holdings from the amount of Treasuries outstanding. Panel (4) of Table 5.4 shows that using this modified version of debt outstanding leaves our results virtually unchanged. In addition, we replace the amount of reserves with the amount of non-Treasury securities held by the Fed. This measure can capture changes in reserves that leave the publicly-available Treasury debt unaffected and Panel (5) shows that it has a qualitatively similar impact on SOFR as reserves.

The Impact of Financial Regulation

We next test if the introduction of the LR in January 2013 (more precisely, the reporting of the LR to regulators from 2013 on) impacted rates. Because SOFR is only backward calculated until August 2014 and because the tri-party repo rate is only available from September 2012 on, we focus our analysis of the pre-2013 period on the GCF repo rate. We contrast the month-end and quarter-end spikes in the 2010–2013 period with the 2013–2019 period and find massive average quarter-end spikes of 18.55 basis points in the post-2013 period, which did not exist before. This behavior is opposite to the pre-crisis results reported in Bartolini et al. (2010), who find significant *downward* spikes in the GCF repo rate at quarter-ends. Panel (2) of Table 5.5 shows the results for the tri-party repo rate in the 2013 – 2019 period; the rate exhibits a less significant volatility at quarter-ends than the GCF rate. As explained in Section 5.2, any potential downward spikes in tri-party repo rates are limited by the Fed reverse repo program, while quarter-end spikes in other repo market segments could spill over to the tri-party market.

Panels (3) and (4) illustrate the mechanisms in the repo market from a different angle, using the difference between quarter-end and quarterly average repo holdings for individual banks as independent variable. We regress this measure on a dummy variable (FBO) that equals one if the bank is a foreign banking office and zero otherwise, and a post-2013 dummy variable, interacted with FBO. The idea behind this test is that, in contrast to U.S. banks, who report quarterly averages, foreign bank offices report quarter-end snapshots of their leverage ratio to regulators. With the beginning of leverage ratio reporting to regulators in 2013, we therefore expect an impact on foreign banking offices that is not present for U.S. banks.

Panels (3) and (4) show the regression results for repo borrowing and repo lending, respectively. Panel (3) shows that, in the post-2013 period, foreign banking offices reduce their quarter-end borrowing significantly compared to U.S. banks, suggesting that foreign bank offices engage in window dressing to increase their Leverage ratio over reporting dates. Panel (4) shows a qualitatively similar, but weaker, pattern for repo lending. The weaker result is in line with repo lending being, in principle, balance sheet neutral and only affecting constraints due to repo intermediation.

5.4 Implications for Term Rates

In this section, we first examine how term rates based on the alternative benchmarks deviate from term rates. We then study the transition of derivatives markets toward the alternative benchmarks and conclude with an overview of the implications for discount rates.

5.4.1 Comparison to Term LIBOR

An important difference between term (tenors with more than one day to maturity) and term rates based on the alternative benchmarks is that contains a term premium. This term premium comprises a liquidity premium to compensate lenders for committing funds over longer time periods and a credit premium accounting for the risk that the borrower defaults during the term of the loan (see Filipović and Trolle, 2013 for a decomposition of the term premium in).[17] By contrast, term rates based on the alternative benchmarks will be averages of overnight rates and therefore lacking a term premium.

To illustrate the different ways of averaging the alternative benchmarks, assume that we want to compute a 3-month term rate. The simplest approach is to compute the average of the overnight rate over the past 90 days. This approach is also called averaging “in advance” because the resulting term rate is available in advance of a payment.[18] Averaging in advance has the shortcoming that it results

[17] In theory, even overnight rates can contain a credit premium, but for borrowers with high credit quality, the default risk decreases with shorter times to maturity. Hence, the credit premium is negligible for overnight rates.

[18] One example of such term rates are the SOFR term rates published by the New York Fed (`https://apps.newyorkfed.org/markets/autorates/sofr-avg-ind`)

in a backward-looking rate that, unlike , does not reflect market expectations about interest rates in the following 3 months. An alternative approach partly addressing this shortcoming is averaging "in arrears" – in our example that means computing the 3-month term rate as average overnight rate over the following 90 days. Despite the drawback that these in arrears averages are not available in real time and reflect realized instead of expected rates, regulators explicitly advocate the use of this approach (see, for example, ARRC (2019); "A users guide to SOFR"). A third approach is extracting forward-looking averages from derivatives, which would incorporate future rate expectations and be available in advance. However, the drawback of this approach is that derivatives prices are not as robust as transaction-based overnight rates. In theory, dealer banks could collude to manipulate the derivatives prices which would undermine the fact that the underlying overnight rate fulfills all the requirements to a robust benchmark rate.

In addition to choosing between in advance and in arrears averaging, we also need to distinguish two different ways of computing averages – compounding the interest as a geometric average $\frac{360}{N}[\prod_{i=1}^{N}\left(1+\frac{1}{360}r_i\right)-1]$ or simple averaging as $\frac{1}{N}\sum_{i=1}^{N} r_i$, where N is the time period over which rates are compounded. We use simple averaging to compute averages in arrears and provide summary statistics of the spread between term rates based on the new benchmarks and 3-month LIBOR rates in Panel (b) of Figure 5.1. As we can see from the figure, the median spread is negative in all three rates and significantly lower than the spreads in Panel (a), which compared the alternative benchmarks to overnight .

To better understand the spread between term rates based on averaging the alternative benchmarks ($\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON}$) and term ($\ell_t^{3m}$), we next decompose the spread into two components – a proxy for the term premium and the benchmark spread:

$$\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON}-\ell_t^{3m}=\underbrace{\left(\frac{1}{90}\sum_{i=1}^{90}\ell_{t+i}^{ON}-\ell_t^{3m}\right)}_{\approx\text{ Term premium}}+\underbrace{\left(\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON}-\frac{1}{90}\sum_{i=1}^{90}\ell_{t+i}^{ON}\right)}_{\approx\text{ Benchmark spread}}. \tag{5.2}$$

The resulting proxy for the term premium has three components – in addition to the liquidity premium and credit premium discussed above, it also contains an "expectations error" because the in arrears average of overnight reflects the realized level of interest rates while 3-month reflects the market expectation for rates over the next three months (this error is not present when using OIS contracts instead).

Figure 5.5 shows the results of this decomposition. As we can see from the figure, the term premium occasionally exceeds -50 basis points in the U.S., reaches almost -40 basis points in the U.K.,and is between 0 and -5 basis points in Europe. In addition, Figure 5.5 shows that the U.S. benchmark spread exhibits large variation between -20 and 15 basis points, with a noticeable spike in mid-2019 while the benchmark spread in the U.K. is relatively stable with the only noticeable change in 2018, when the reform lead to a decrease in rates. In Europe, the term spread is virtually constant at 8.5 basis points and significantly larger than the term premium.[19]

5.4.2 The Impact on Derivatives Markets

We next examine how the Libor funeral affects the open interest of Euro-dollar futures for contracts referencing either USD , GBP , or Euribor. Euro-dollar futures are exchange-traded derivatives that pay the 3-month or Euribor rate at expiry (which is the third Wednesday of a quarter). The price of each futures contract reflects the expected 3-month (or Euribor) rate at a future valuation date and contracts with valuation dates up to 60 months in the future are liquidly traded in all three currencies.

Focusing on the open interest of Euro-dollar futures allows us to test if market participants reduced their exposure in contracts with valuation dates after December 2021 once Bailey (2017) announced the funeral on July 27, 2017. Table 5.6 shows the results of regressing the log-open interest in contracts with valuation dates between 27 and 60 months on the interaction between a dummy variable that equals one after the funeral announcement ($1_{t>Funderal}$) and a dummy variable that equals one if the valuation date of the underlying contract is after December 2021 ($1_{T>Discontinued}$). We remove contracts with less than 27 months to maturity to keep the focus on contracts that reference after December 2021 at least once during our January 2015 – December 2019 period. To control for potential differences in open interest for contracts with different maturities, we add time-to-maturity (TTM) fixed effects. In addition, each specification includes year fixed effects, $1_{t>Funderal}$, and $1_{T>Discontinued}$ as controls.

If market participants reduced their exposure after the funeral announcement, we would expect a negative coefficient on the interaction term. However, as we can see from Panel (1) of Table 5.6, the funeral had no significant effect on USD futures contracts that reference after December 2021. By contrast, Panel (2) suggests that the open interest in GBP contracts with valuation dates after December 2021 dropped after the funeral while Panel (3) suggests the opposite is true for Euribor futures, where the open interest increased. The increase for Euribor futures reflects the different approach of European regulators, who decided to reform Euribor instead of discontinuing it after 2021 (see EMMI, 2018). Moreover, the significant decrease for GBP contracts is in line with Sonia derivatives already being liquidly traded and therefore allowing investors to transition away from . By contrast, activity in Sofr-linked derivatives is picking up slowly, which can explain the insignificant drop in USD futures. Confirming the different developments in derivatives markets, ISDA (2020) estimates that 31.8% of the risk in OTC interest rate derivatives for GBP are already linked to Sonia while only 3.8% of USD derivatives are linked to Sofr.

[19] The missing term premium in the alternative benchmarks makes it difficult to compare term rates based on averaging the alternative benchmarks with other proxies for the risk-free rate. For instance, Van Binsbergen et al. (2019) derive an option-implied risk-free rate and we compare this option-implied rate to Treasury yields and average Sofr rates in Figure 5.D.1 in the online appendix, showing that the average Sofr rate is significantly lower.

5.4.3 Implications for Discount Rates

To discount future cash-flows and value derivatives, it is common to use a rate that is close to risk-free. Since the financial crisis, market participants such a clearinghouses and derivatives traders rely on overnight index swap (OIS) rates as discount rates (see, for example, Hull and White, 2013). The funeral will impact this practice by changing these discount rates from the current OIS benchmarks to OIS referencing the alternative benchmarks. For the U.K., which uses a reformed version of its OIS benchmark as replacement, this switch is already implemented. In Europe, the old OIS benchmark is Eonia and the transition comprises two steps; from Eonia to Estr plus 8.5 basis points and from Estr plus 8.5 basis points to Estr flat. We discuss the practical implications of this 8.5 basis point switch in Section 5.4.4 and focus this section on implications for U.S. benchmarks.

SOFR-OIS Spreads

In this subsection, we use futures contracts to construct a 3-month Sofr-OIS spread which we compare to the 3-month Libor-OIS spread. To construct this spread, we rely on Fed funds futures and Sofr futures. Fed funds futures are widely-used hedging instruments that mature at the end of each calendar month and reference the arithmetic average of the effective Fed funds rate (Effr) during that month. Sofr futures were introduced in May 2018, reference Sofr instead of the Effr, and, apart from that, have exactly the same contract details as Fed funds futures.[21] We use the implied futures rates in these contracts to construct discount and forward-discount factors that allow us to compute discount factors from the current date to the end of month $t+2$ and the end of month $t+3$. We then use these discount factors to extract corresponding term rates and obtain 3-month Sofr and Effr by interpolating between the rates for month $t+2$ and $t+3$.

Panel (a) of Figure 5.6 compares the resulting 3-month Sofr-OIS spread to the observed 3-month Libor-OIS spread. As we can see from the Figure, the repo squeeze on September 16, 2019 lead to an increase in the Sofr-OIS spread which only normalized after the quarter-end date on September 30, while having virtually no effect on the Libor-OIS spreads. By contrast, in March 2020, when the Corona virus started hitting the U.S. economy – the third red line in Figure 5.6 highlights the date when the Fed cut interest rates by 50 basis points – we see a sharp increase in Libor-OIS spreads while Sofr-Effr spreads show a moderate initial increase. During March 2020, we then observe a further increase in Libor-OIS spreads while Sofr-Effr spreads reverse into negative. These increases in combined with decreases in Sofr resonate with Schrimpf and Sushko (2019), who argue that the difference between and collateralized rates becomes most apparent in crisis times.

To better understand the term rate during this turbulent period, Panel (b) shows the spread between overnight Sofr and Effr. As we can see from the figure, the overnight Sofr-Effr spread spiked above 150 basis points at the September repo squeeze followed by an increase to around 50

[21] In addition to this type of Sofr futures, there is a second type which closely resembles Euro-Dollar futures, referencing the three-month average Sofr and maturing at the same dates as Euro-dollar futures. We provide additional detail on this type of futures in Appendix 5.A.

basis points at quarter-end in late September. In early March 2020, the volatility of the SOFR-EFFR spread starts increasing with the onset of the crisis. On March 12 (fourth red line), the Fed's term repo program schedule was announced and on March 17 the Fed announced the overnight repo program (announcing 500 billion of overnight repo lending every day), which stabilized repo markets and lead to a drop of the SOFR-FFR spread into negative territory. Taken together, Figure 5.6 highlights a fundamental difference between LIBOR rates and SOFR – during a crisis period, repo rates do not increase as significantly as uncollateralized bank lending.

Spikes in SOFR Term Rates

We next use SOFR futures to examine spikes in SOFR term rates. We first focus on SOFR-EFFR futures spreads and contracts with maturities between 2 months and 6 months, removing the 1-month contract (because we are interested in expectations about future term rates) and dropping less liquid contracts with more than 6 months to maturity. We then examine if the futures-implied SOFR-EFFR spread is higher for contracts that expire in the last month of the quarter or the last month of the year. Panel (1) of Table 5.7 shows that this is indeed the case; the average SOFR-EFFR futures spread is positive at 3.44 basis points and 0.79 basis points higher in the last month of the quarter and more than 2 basis points ($0.79 + 1.39$) higher in the last month the calendar year. Panel (6) shows that this results remains virtually unchanged after adding year-quarter and maturity-type fixed effects.

Because the EFFR can be prone to downward spikes at regulatory reporting dates (see our discussion in Internet Appendix 5.B), part of the quarter-end and year-end spikes in Panels (1) and (2) could be a result of expected downward spikes in the EFFR instead of expected upward spikes in SOFR. We therefore use an alternative approach to examine expected quarter-end spikes in SOFR. Similar to Fleckenstein and Longstaff (2019), who examine year-end effects in Euro-dollar futures, we construct an interpolated SOFR futures rate for month t by linearly interpolating between SOFR futures rate in month $t-1$ and in month $t+1$ and then examine the spread of the SOFR-implied futures rates for month t and the interpolated rate. As we can see from Panels (3) and (4) in Table 5.7, this approach leads to qualitatively similar but less significant results. Given that downward spikes in the EFFR are much smaller than the upward spikes in SOFR and diminish after Q2 2018 (our futures sample starts in May 2018), we argue that the SOFR-EFFR spreads in Panels (1) and (2) more closely reflect the expected quarter-end behavior of SOFR than the simple spline estimates in Panels (3) and (4).

5.4.4 Practical Issues Going Forward

We now discuss six practical issues stemming from the funeral.

First, even though market participants know the overnight rates set to replace , the construction of corresponding term rates can vary across market segments. For example, USD interest rate swaps and floating rate notes (FRNs) reference Sofr compounded averages in arrears, syndicated loans reference Sofr simple averages in arrears, and mortgage-backed securities (MBS) reference Sofr compounded in advance. Moreover, the ARRC recommends in arrears averaging for business loans (see ARRC, 2020a) while this approach is not possible for mortgages where regulation requires that consumers know their interest rate 45 days in advance. Complicating the transition further, compounded Estr is problematic for Germany and Italy, where compounded interest is illegal in consumer loans (see Smith, 2019). The difference between in arrears and in advance compounding can be substantial when key policy rates change unexpectedly while the difference between simple averaging and compounding is negligible, especially when interest rates are low (see ARRC, 2020b).

Second, the fact that term rates based on alternative benchmarks are detached from banks' marginal funding costs (especially for the U.S., where term spreads are high), poses a problem for bank loans – was originally introduced as benchmark in syndicated loans, allowing banks to charge a spread relative to their own funding costs (see, Vaughan and Finch, 2017). Replacing the floating rate in a loan with an overnight rate exposes banks to fluctuations in term premiums and be especially problematic for products like credit lines, where the probability of customers drawing on such lines increases during market turmoil. These issues contributed to a slow growth in Sofr-denominated debt, mainly issued by U.S. agencies so far (see Smith, 2020a) and opposed by smaller banks (see Banker, 2020) and received heightened attention during the market turmoil in March 2020 when spreads soared. To resolve these issues, the U.S. established a credit sensitivity group (CSG) and a likely fix is constructing a measure of bank credit risk that can be added to Sofr (see Berndt et al., 2020 for one proposal and a discussion of this approach).

Third, changing the reference rate in the vast quantity of derivatives referencing and maturing after 2021 is a challenge. One possible solution is to determine the compensation for switching the underlying derivatives benchmark from to alternative benchmarks in an auction, thereby retiring large parts of derivatives before December 2021 (see Duffie, 2018b or Zhu, 2019 for a discussion of different mechanisms). The International Swaps and Derivatives Association (ISDA), suggests amending the derivatives contracts with a fallback protocol: Should be discontinued the benchmark rate will be replaced with the alternative benchmark, compounded in arrears, plus a fallback spread. The fallback spread is the five-year historical median spread between and the compounded alternative benchmark (see ISDA, 2019). As discussed in Section 5.4.2, dervatives trading transitions slowly to referencing the alternative benchmarks and to increase trading volumes in derivatives referencing the alternative benchmarks, the U.S. Treasury is considering to issue FRNs linked to Sofr (see Zhu, 2020 for a comment on this idea). In addition, clearing houses change the discount rates for derivatives pricing and collateral valuation from OIS discounting (with the Effr or Eonia as benchmark in the U.S. and Europe, respectively) to using discount rates based on the alternative benchmarks.

Fourth, this discounting switch poses a challenge for derivatives markets in the U.S. and Europe. In Europe, the Eonia reform first replaces Eonia with Estr plus 8.5 basis points, reflecting the almost constant spread between EONIA and ESTR. In a second step, ESTR plus 8.5 basis points is replaced by ESTR flat. This 8.5 basis point switch in discount rates changes the valuation of interest rate swaps and other derivatives. While regulators can impose a compensation scheme for cleared derivatives, the compensation scheme is voluntary for uncleared derivatives. This is especially problematic for levered swap positions such as options to engage in swaps (commonly known as swaptions), where changes in discount rates can lead to windfall profits or losses (see Becker, 2020). In addition to these potential windfall profits, the situation in the U.S. is challenging because SOFR-EFFR spreads are more volatile.

Fifth, while the construction of LIBOR is similar across countries, the construction of the new benchmark rates differs across countries and the rates exhibit quantitatively different patterns. Hence, in addition to the basis risk between LIBOR and the new benchmark rates, the LIBOR funeral also introduces additional basis risk across countries. This basis risk can be amplified by different conventions for obtaining term rates in different regions (see Smith, 2020b).

Finally, the funeral poses difficulties for the risk management of U.K. insurance companies. On the one hand, the financial conduct authority (FCA) urges insurances to transition away from (see the FCA "Dear CEO Letter") while insurance regulation under Solvency II explicitly uses discount rates linked to swap rates. Hence, U.K. insurers using SONIA derivatives instead of LIBOR derivatives can face regulatory capital charges for transitioning to the alternative benchmarks.

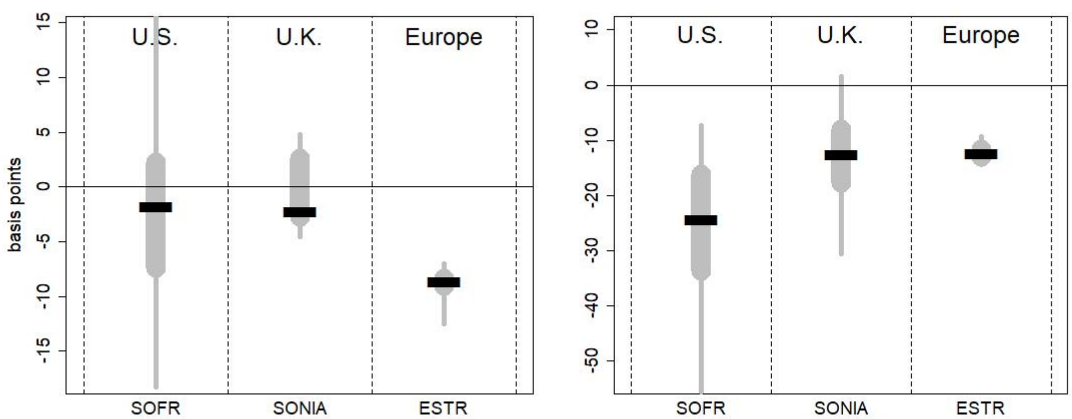
5.5 Concluding Remarks

We examine the alternative benchmark rates in the U.S., the U.K, and Europe, provide a detailed overview of the micro-structure behind these rates, and highlight their three main drivers. First, tighter regulatory constraints increase SOFR but decrease SONIA and ESTR. Second, besides the predictable reporting date spikes, a higher volume of government debt outstanding corresponds to a significant increase in SOFR and less-significant increases in SONIA and ESTR. Finally, when reserves are at a low level, an increase in the amount of reserves lowers the alternative benchmarks. Our analysis provides a better understanding of the alternative benchmark rates which is important given that these rates are intended to replace LIBOR in trillions of loans, floating rate debt, and financial contracts. In addition, we show that term rates based on the alternative benchmark rates can be affected by regulatory reporting spikes but are more stable than LIBOR rates, lacking a term premium.

While the transition away from LIBOR to alternative benchmark rates will enhance the transparency and robustness of benchmark rates, our paper highlights three potential issues for the "life after LIBOR". First, the type of transactions underlying the alternative benchmarks affect the interest rates and introduce volatility unrelated to banks' marginal funding costs. More broadly, while the inclusion of non-bank to bank transactions in the alternative benchmarks ensures that transaction volumes are robust, borrowing from non-banks might not be readily available for some banks, putting a wedge between the rates and banks' marginal funding costs. Second, we show that the supply of government debt affects the alternative rates. For collateralized rates, the impact of government debt supply is even more pronounced because the rates are also affected by the availability of government debt collateral. Finally, term rates based on the alternative benchmarks lack a term premium, which detaches these rates from banks' costs of term funding and introduces problems for loan issuance.

Figures and Tables

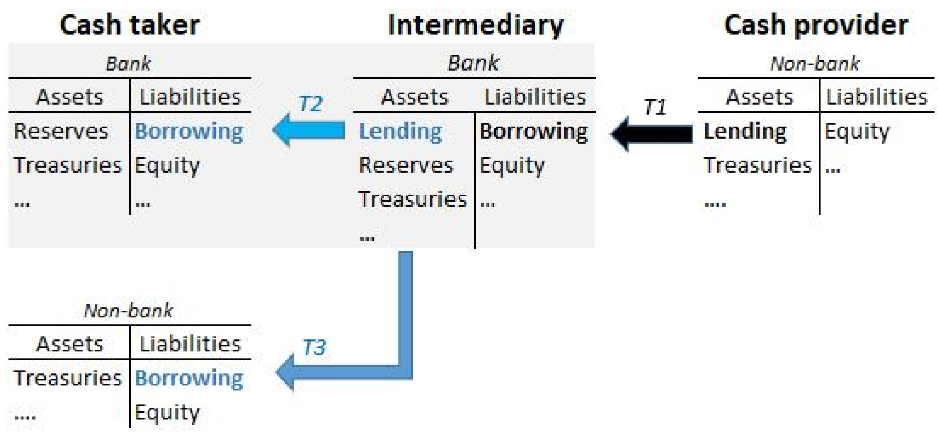
Figure 5.1
Spread between the alternative benchmark rates and LIBOR



(a) Overnight spreads (b) Term spreads using 3m average

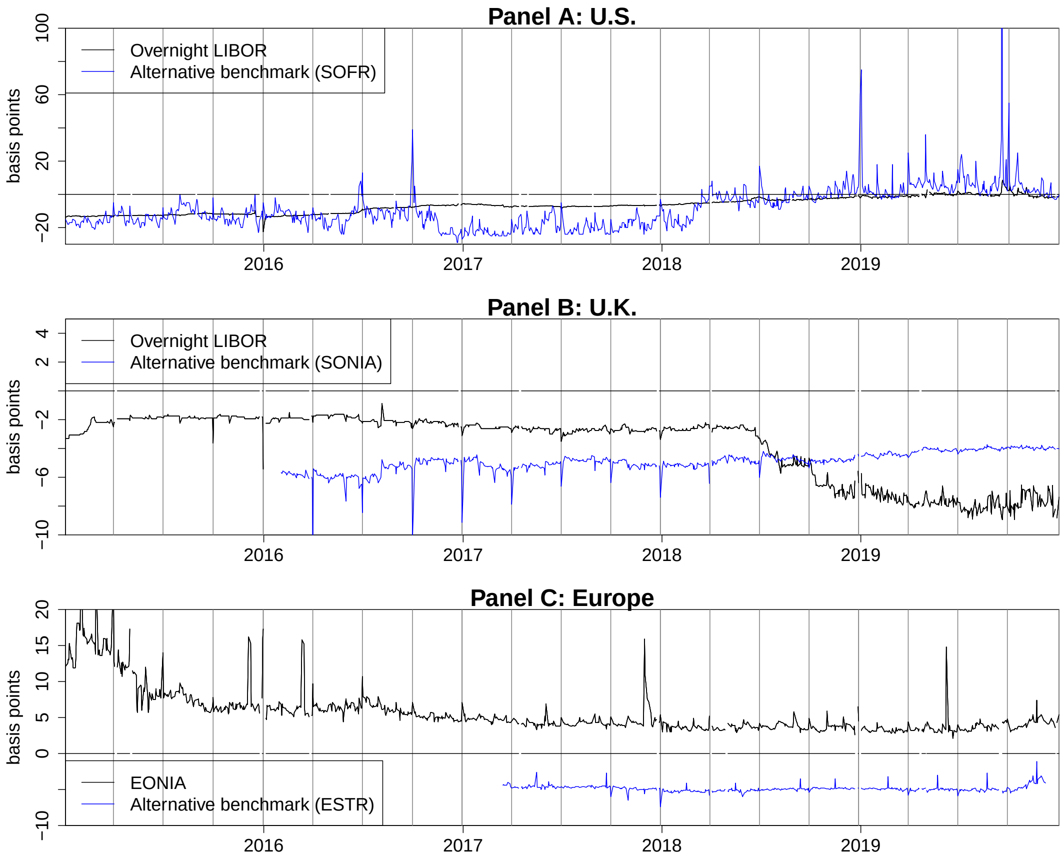
Notes: This figure shows medians (black bars), ranges between the 25% and 75% quantile (thick grey line), and ranges between the 1% and 99% quantiles (thin grey line) for the spread between the alternative benchmark rate in the U.S., the U.K., and Europe relative to LIBOR (for the U.S. and the U.K.) or EURIBOR (for Europe). Panel (a) shows the spread between the alternative benchmark rates and the overnight LIBOR rate (for the U.S. and the U.K.) or the spread relative to EONIA (the overnight EURIBOR rate for Europe). Panel (b) shows the spread between 3-month forward-looking averages of the alternative benchmark rates, computed in arrears, and 3-month LIBOR (for the U.S. and the U.K.) or EURIBOR (for Europe). The sample periods starts in August 2014 for the U.S., February 2016 for the U.K., and December 2016 for Europe and include data until December 2019.

Figure 5.2
The different transaction types in the alternative benchmarks



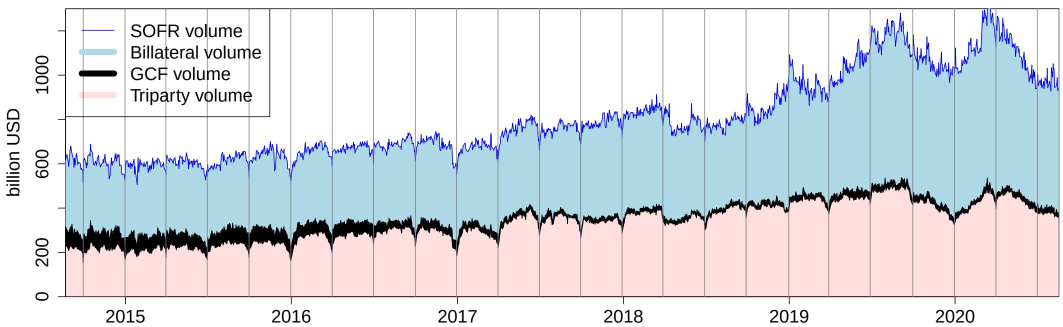
Notes: This figure gives a stylized overview of the different types of transactions that can be part of the alternative benchmarks, abstracting from whether the underlying transaction is collateralized or uncollateralized. The figure shows lending from right to left, starting with a non-bank cash provider who lends to a bank (*T1*) that acts as intermediary and, in turn, lends to a cash taker. The cash taker can either be another bank (*T2*) or a non-bank (*T3*). The grey area highlights the interbank transactions.

Figure 5.3
Alternative benchmarks and overnight Libor in different regions



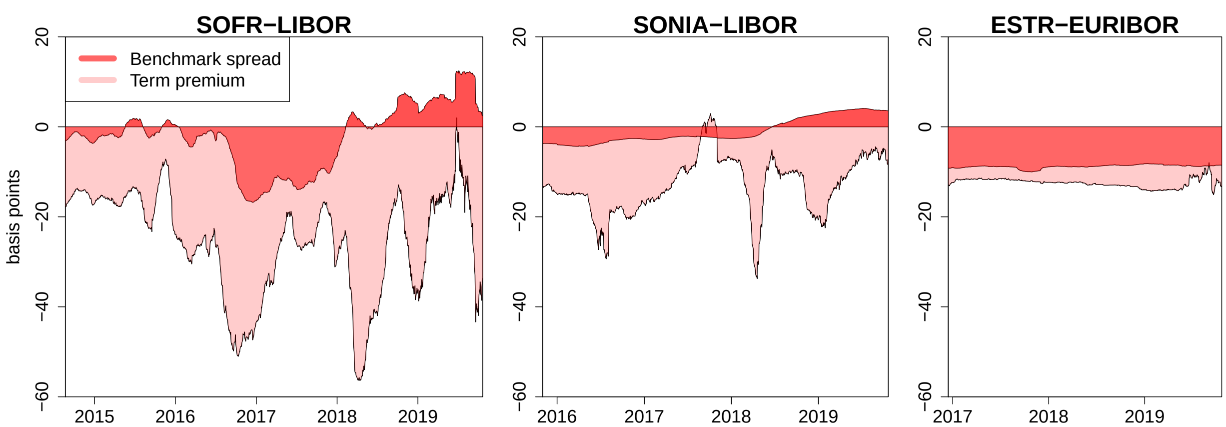
Notes: This figure compares the level of the alternative benchmark rates (blue lines) in the U.S., the U.K., and Europe to the overnight LIBOR rates (for the U.S. and the U.K.) or EONIA (the overnight EURIBOR rate for Europe). To remove the effect of changes in policy target rates, each line represents the spread between an overnight rate and a proxy of the policy target rate in the respective region. These policy targets are the interest on excess reserves (IOER) for the U.S., the "bank rate" at which banks can deposit money with the Bank of England for the U.K., and the rate that banks receive for placing their reserves with the European central bank for Europe. The grey vertical lines indicate quarter-ends.

Figure 5.4
Underlying repo volumes in SOFR



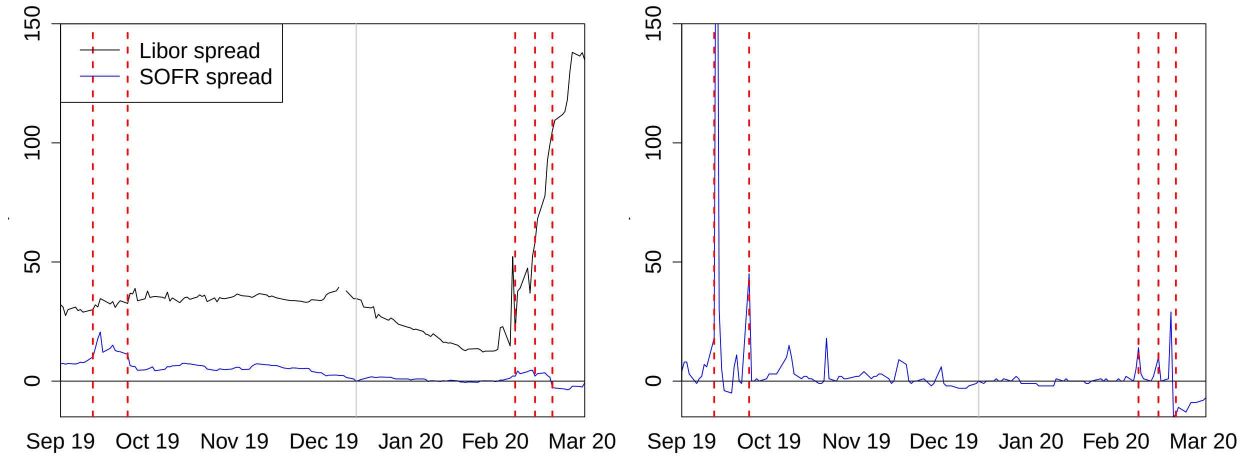
Notes: This figure shows the volumes of the different types of repo transactions underlying SOFR. The three different types are (from top to bottom): Billateral repo volumes, GCF repo volumes, and Triparty repo volumes. The grey vertical lines indicate quarter-ends.

Figure 5.5
Spread between 3-month average of alternative benchmarks and LIBOR



Notes: This figure decomposes the spread between 3-month averages of the alternative benchmarks, computed in arrears, and 3-month LIBOR into a term spread component and benchmark spread component. The light-shaded areas show the component of the spread due to term premium. This component is estimated as the spread between the 3-month average of overnight (or EONIA; both computed in arrears) and 3-month term . The dark-shaded areas show the component of the spread due to differences in overnight rates. This component is computed as the 3-month average of the spread between the alternative benchmarks and overnight . On days where the spread between overnight rates is positive, the term premium is the sum of the light-shaded and dark-shaded areas in the graph. On days where the term premium component is positive, the term premium is the sum of the light-shaded and dark-shaded areas in the graph.

Figure 5.6
Spreads relative to the EFFR



(a) 3-month spread (b) Overnight spread

Notes: Panel (a) shows the spread between the 3-month SOFR rate and 3-month Fed funds rate, extracted from SOFR and Fed funds futures as well as the spread between 3-month LIBOR and the 3-month OIS rate based Fed funds. Panel (b) shows the spread between overnight SOFR and the Fed funds rate. We focus on the September 2019 – March 2020 period and the red lines highlight the repo squeeze on September 16, 2019, the quarter-end date September 30, 2019, the rate cut by 50bp on March 4, 2020, the introduction of the Fed term repo program on March 12, 2020, and the announcement of the Fed overnight repo program on March 19, 2020.

Table 5.1
Properties of the alternative benchmark rates

	Panel A: Background			**Panel B:** Impact on rates		
Name	Transactions included	Alternatives for non-bank lenders	Collateralized	Regulatory constraints	More Treasuries	More reserves
SOFR	*T1*, *T2*, *T3*	Fed's RRP	51	↑	↑	↘
SONIA	*T1*, *T2*	55	55	↘	↗	↘
ESTR	*T1*, *T2*	55	55	↘	↗	↘

Notes: Panel A gives an overview of the background behind the alternative benchmark rates in the U.S. (SOFR), the U.K. (SONIA), and Europe (ESTR). Panel B summarizes how regulatory constraints, a larger quantity of Treasury debt, and more central bank reserves affect the different rates.

Table 5.2
Reporting-date spikes in the alternative benchmark rates

	SOFR		SONIA		ESTR	
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	−2.39***		−4.89***		−4.81***	
	(−7.87)		(−242.31)		(−158.90)	
QEnd	20.25***	20.00***	−2.12***	−2.04***	−0.51***	−0.57***
	(4.73)	(5.39)	(−2.68)	(−3.29)	(−2.83)	(−3.45)
YEnd	−2.20	−1.27	0.61	0.33	−1.57***	−1.48***
	(−0.22)	(−0.14)	(0.48)	(0.31)	(−3.97)	(−3.97)
MEnd \ QEnd	10.06***	10.10***	−0.38**	−0.39***	−0.16	−0.16
	(9.25)	(10.19)	(−2.35)	(−5.07)	(−1.26)	(−1.52)
FEs	–	YQ	–	YQ	–	YQ
Adj. R^2	0.07	0.29	0.11	0.75	0.02	0.13
Num. obs.	1,337	1,337	987	987	695	695

Notes: This table shows the results of regressing the alternative benchmark rates on three dummy variables capturing regulatory reporting dates. QEnd equals one on the last trading day of a quarter and zero otherwise, YEnd equals one on the last trading day of a year and zero otherwise, and MEnd \ QEnd equals one on the last trading day of a month which is not quarter-end and zero otherwise. Panels (2), (4), and (6) include year-quarter fixed effects. The independent variables are SOFR (Panels (1) and (2)), SONIA (Panels (3) and (4)), and ESTR (Panels (5) and (6)). To remove fluctuations in these rates due to changes in policy rates, we use the spread of these rates over the policy targets in the three regions. The sample periods start in August 2014 for SOFR, February 2016 for SONIA, and December 2016 for ESTR, including data until December 2019. The numbers in parantheses are Newey-West *t*-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Table 5.3
Drivers of the alternative benchmark rates in the U.K. and Europe

	SOFR		SONIA		ESTR	
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	−0.00***	−0.01	0.00	0.00	−0.00	0.00
	(−2.91)	(−1.50)	(0.11)	(0.41)	(−0.19)	(0.33)
$\Delta \log(Debt)$	9.73***	4.00***	0.06**	0.01	−0.21	0.07
	(8.80)	(3.03)	(2.01)	(0.37)	(−1.09)	(1.14)
$\Delta \log(Transact.\ Volume)$	0.09**	0.20***	0.00	0.00*	0.02***	0.02***
	(2.46)	(2.68)	(1.22)	(1.85)	(4.10)	(3.92)
$\Delta \log(Reserves)$		−0.14		0.01		−0.03
		(−1.15)		(0.74)		(−1.47)
Adj. R^2	0.12	0.07	0.01	0.00	0.06	0.22
Num. obs.	1,186	241	850	179	597	124

Notes: This table shows the results of regressing changes in the alternative benchmark rates on the indicated variables. Panels (1), (3) and (5) examine daily changes. Panels (2), (4) and (6) examine weekly changes (sampled on Wednesdays). For the U.S., the U.K., and Europe, $\Delta \log(Debt)$ are changes in the total amount of U.S. Treasuries, Gilts, or German Treasuries outstanding, respectively. $\Delta \log(Transact.\ Volume)$ are changes in the total trading volume underlying the alternative benchmark rates, and $\Delta \log(Reserves)$ are changes in the total amount of bank reserves in the respective area. The independent variables are SOFR (Panels (1) and (2)), SONIA (Panels (3) and (4)), and ESTR (Panels (5) and (6)). To remove fluctuations in these rates due to changes in policy rates, we use the spread of these rates over the policy targets in the three regions. The last, second-last, and first trading day of each month as well as five days after September 15 are removed from the sample to avoid large outliers and reporting-date spikes driving the results. The sample periods start in August 2014 for SOFR, February 2016 for SONIA, and December 2016 for ESTR, including data until December 2019. The numbers in parantheses are heteroskedaticity-robust t-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Table 5.4
What makes SOFR tick?

	(1)	(2)	(3)	(4)	(5)
Intercept	-0.00^{***}	-0.01	-0.01	-0.01	-0.01^{*}
	(-3.03)	(-1.31)	(-1.34)	(-1.51)	(-1.93)
$\Delta \log(Debt)$	10.17^{***}	3.56^{**}	3.43^{**}		
	(11.25)	(2.39)	(2.45)		
$\Delta \log\left(\frac{TPV}{SOFRV}\right)$	-0.07^{***}	-0.08	-0.09	-0.08	-0.11
	(-2.80)	(-1.08)	(-1.30)	(-1.05)	(-1.52)
$\Delta \log(PD\ NetRepo)$		0.21^{***}	0.20^{***}	0.20^{***}	0.20^{***}
		(3.51)	(3.48)	(3.33)	(3.22)
$\Delta \log(Reserves)$		-0.26^{*}	-0.08	-0.24^{*}	
		(-1.90)	(-0.56)	(-1.80)	
$\Delta \log(Reserves) \times 1_{\geq Jul\ 2018}$			-0.94^{***}		
			(-2.64)		
$\Delta \log(Debt \setminus FED)$				3.39^{***}	3.79^{***}
				(2.94)	(3.51)
$\Delta \log(Other\ Hold)$					-1.53^{*}
					(-1.79)
Adj. R^2	0.13	0.08	0.11	0.08	0.09
Num. obs.	1,135	235	235	235	235

Notes: This table shows the results of regressing changes in SOFR on the indicated variables. To avoid capturing fluctuations in SOFR due to changes in the policy target rate, we analyze the spread between SOFR and the upper bound of the of the Federal Fund's target rate. $\Delta \log(Debt)$ are changes in the total amount of Treasuries outstanding, $\Delta \log(TPV/SORFV)$ are changes in the fraction of triparty repo in SOFR, $\Delta \log(PD\ NetRepo)$ are changes in the net amount of overnight repos of primary dealers, $\Delta \log(Reserves)$ are changes in the total amount of bank reserves in the U.S., $1_{\geq Jul\ 2018}$ is a dummy variable that equals from July 2018 on and zero otherwise, $\Delta \log(Debt \setminus FED)$ are changes in the amount of Treasuries outstanding minus FED Treasury holdings, and $\Delta \log(Other\ Hold)$ are changes in the amount of non-Treasury securities on the FED balance sheet. Panel (1)examines daily changes, Panels (2)–(5) examine weekly changes (sampled on Wednesdays). The last, second-last and first trading day of each month as well as five days after September 15 are removed from the sample to avoid reporting-date spikes or the large September 15, 2019 spike driving the results. The sample period is August 2014 to December 2019. The numbers in parantheses are Newey-West t-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Table 5.5
Changing reporting-date effects in U.S. rates

	GCF (1)	TPR (2)
QEnd	0.93	
	(0.39)	
YEnd	−4.40	
	(−1.11)	
MEnd $\setminus$ QEnd	3.92***	
	(4.29)	
QEnd × $1_{\{\geq 2013\}}$	18.55***	9.15***
	(3.90)	(3.54)
YEnd × $1_{\{\geq 2013\}}$	29.27	0.29
	(0.85)	(0.04)
MEnd $\setminus$ QEnd × $1_{\{\geq 2013\}}$	1.98	4.50***
	(1.41)	(3.68)
Adj. R^2	0.33	0.27
Num. obs.	2,498	1,337

	Borrowing (3)	Lending (4)
Intercept	−0.91**	−0.57*
	(−2.19)	(−1.72)
FBO	0.78*	−0.24
	(1.83)	(−0.60)
$1_{t\geq 2013}$	0.55	0.46
	(1.58)	(1.62)
FBO $\times 1_{t\geq 2013}$	−0.97**	−0.83
	(−2.08)	(−1.58)
Adj. R^2	0.00	0.00
Num. obs.	21,979	21,887

Notes: Panels (1) and (2) show the results of regressing the spread between GCF or triparty repo rates and the IOER rate on three dummy variables: QEnd, which equals one on the last trading day of a quarter and zero otherwise, YEnd, which equals one on the last trading day of a year and zero otherwise, and MEnd $\setminus$ QEnd, which equals one on the last trading day of a month that is not quarter-end, and zero otherwise. $1_{\geq 2013}$ is a dummy variable that equals one if the observation is after January 2013 and zero otherwise. Both specifications include year-quarter fixed effects. The sample period is January 2010 to December 2019. Panel (3) and (4) show the results of regressing the difference between banks repo holdings (borrowing and lending) on quarter end and the quarterly average during the quarter on $1_{\geq 2013}$ and FBO, which equals one if the bank is a foreign banking office operating in the U.S. and zero if it is a U.S. bank. The sample period is first quarter 2000 to fourth quarter 2018. The data is obtained from regulatory filings to Federal Financial Institutions Examination Council's (FFIEC). The numbers in parantheses are Newey-West t-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Table 5.6
The impact of the Libor funeral of futures volumes

	USD	GBP	Euribor
$1_{\{t>Funeral\}} \times 1_{\{T>Discontinue\}}$	−0.03	−0.60**	0.40***
	(−0.46)	(−2.20)	(4.69)
$1_{\{t>Funeral\}}$	−0.02	0.06	−0.06
	(−0.36)	(0.38)	(−0.63)
$1_{\{T>Discontinue\}}$	−0.02	1.80***	−0.04
	(−0.28)	(8.84)	(−0.50)
TTM FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Adj. R^2	0.93	0.87	0.95
Num. obs.	14,592	14,545	14,568

Notes: This table shows the results of regressing the logarithm of the open interest in futures contracts with maturities between 27 and 60 months on three dummy variables. $1_{t \geq Jul/2017}$ is a dummy variable that equals one after the funeral announcement in July 2017 and zero otherwise. $1_{T>Dec2021}$ is a dummy variable that equals one if the contract expires after December 2021 and zero if it expires earlier. Panels (1) and (2) show the results for USD futures. Panels (3) and (4) show the results for GBP futures. Panels (5) and (6) show the results for Euribor futures. All panels include time-to-maturity (TTM) type fixed effects and year fixed effects. The numbers in parantheses are Newey-West t-statistics, clustered at the date and type level. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Table 5.7
Reporting-date spikes in SOFR futures

	SOFR-FFF		SOFR-Spline	
	(1)	(2)	(3)	(4)
Intercept	3.44***		−0.27***	
	(188.00)		(−2.66)	
QEnd	0.79***	0.94***	0.61**	0.45
	(3.42)	(4.90)	(2.25)	(1.56)
YEnd	1.39***	1.16***	0.43**	0.91***
	(2.97)	(2.69)	(2.06)	(3.53)
FEs	–	YQ & Type	–	YQ & Type
Adj. R^2	0.07	0.63	0.01	0.03
Num. obs.	2,060	2,060	2,060	2,060

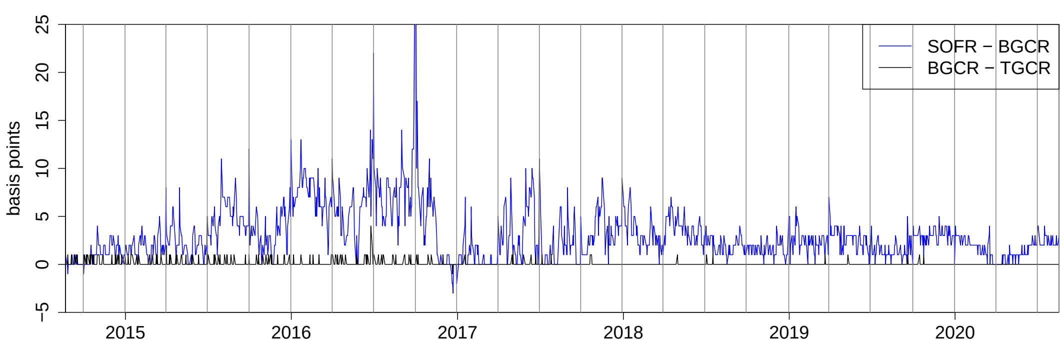
Notes: This table shows the results of regressing the spread between monthly SOFR futures and either Fed Funds Futures (Panels (1) and (2)) or the interpolated SOFR futures rate for contracts maturing in month $T-1$ and $T+1$ (Panels (3) and (4)) for 2, 3, 4, 5, and 6 months to maturity on two dummy variables: QEnd equals one if the contracts expire in the last calendar month of a given quarter and zero otherwise, and YEnd equals one if the contracts expire in the last calendar month of a given year and zero otherwise. The sample comprises daily observations for the May 4, 2018 (the date when SOFR futures trading started) to December 2019 period. The numbers in parantheses are Newey-West t-statistics, clustered by time-to-maturity type. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

Appendix

5.A Additional Details on SOFR

This section contains additional details and descriptive statistics for SOFR. Figure 5.A.1 illustrates the impact of including different market segments into the computation of SOFR. The blue line shows the spread between SOFR and the Broad General Collateral Rate (BGCR), which removes bilateral repo transactions from SOFR. As we can see from the Figure, the SOFR-BGCR is virtually always positive and spikes upward at quarter-ends. Moreover, the black line in Figure 5.A.1 shows the spread between BGCR and the Tri-Party General Collateral Rate (TGCR), which removes GCF transactions from the BGCR. As we can see from the figure, removing GCF transactions has a small effect on the rate, which is in line with the small share of GCF transactions in the overall SOFR volume.

Figure 5.A.1
Different repo rates in SOFR



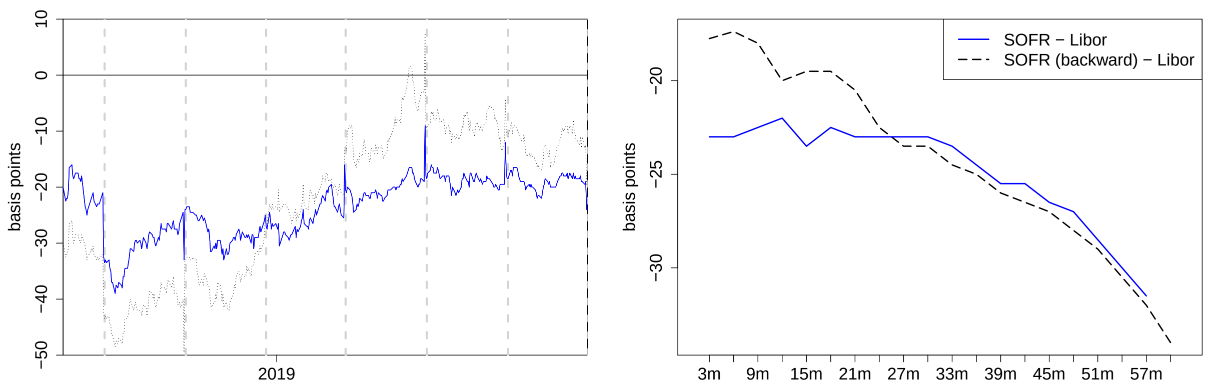
Notes: This figure provides additional background for SOFR, illustrating the spread between SOFR and BGCR (removing billateral transactions) and the spread between BGCR and TGCR, removing GCF transactions. The grey vertical lines indicate quarter-ends.

5.A.1 The Term Structure of SOFR-LIBOR Spreads

We now use Euro-dollar futures and the second type of SOFR futures (the 3-month SOFR futures) to examine the term structure of the SOFR-LIBOR spreads. The 3-month SOFR contracts have the same contract specifications as Euro-dollar futures – they have the same expiry dates, settlement dates, and collateral requirements – but reference the arithmetic 3-month average of the SOFR rate instead of 3-month LIBOR. We use these futures contracts to construct forward-looking spreads, where we match SOFR futures that pay the average SOFR rate over the following three months with Euro-Dollar futures. In addition, we compute backward-looking spreads by using SOFR futures that pay the average SOFR rate over the past three months instead.

Panel (a) of Figure 5.A.2 compares the two spreads for futures contracts with 12 months to maturity. The blue line shows the SOFR-LIBOR spread using forward-looking SOFR futures, while the black-dashed line uses backward-looking SOFR futures. The spread for forward-looking contracts fluctuates between -35 and -15 basis points while the spread for backward-looking contracts is more volatile and fluctuates between -50 and 10 basis points. Panel (b) illustrates the median term structure of SOFR-LIBOR spreads for the May 2018 – December 2019 period. The blue line and black line in Panel (b) illustrate the term structure for forward-looking and backward-looking spreads, respectively. As we can see from the figure, both term structures are downward-sloping, suggesting that investors expect SOFR-LIBOR spreads to be more negative in the long run. Comparing the two term structures, Panel (b) shows that the median forward-looking spread is below the median backward-looking spread for maturities up to 30 months. For the longer end of the term structure, the median spreads are almost identical.

Figure 5.A.2
Spread between different SOFR futures rates and Libor futures rates



(a) 12-month spread (b) Term-structure

Notes: This figure illustrates SOFR-LIBOR spreads extract from 3-month SOFR and Euro-dollar futures contracts. Panel (a) shows the SOFR-LIBOR spread for futures contracts that mature in 12-months. Panel (b) shows the median SOFR-LIBOR spread for different maturities, ranging from 3 months to 60 months. The blue line is the SOFR-LIBOR spread, where forward-looking averages are used and the black line is the SOFR-LIBOR spread, where backward-looking averges are used. The dashed vertical lines in Panel (a) are IMM dates. The sample period is May 2018 to December 2019.

5.B An Illustrative Model

We now illustrate the impact of tighter financial constraints and fluctuations in available government debt on different overnight rates through a simple model. Two types of agents, A and B, can invest in a risky asset in perfectly elastic supply with final payoff $D \sim \mathcal{N}(1+\mu, \sigma^2)$ and price normalized to one. In addition, the agents lend money to each other or invest in government debt with limited fixed supply $\mathcal{S}$. Both government debt and lending between A and B earn the same return r, which we determine below. Moreover, agent B can lend money to another agent (e.g. other bank or hedge fund, which we do not model explicitly) at a rate ρ that we also determine below. Both agents have the same risk aversion γ and agent $G \in \{A, B\}$ maximizes the mean-variance utility of end-of-period wealth W^G:

$$\max_{g,\bar{g}} \left[g(\mu - r - \gamma g \frac{\sigma^2}{2}) + \bar{g}(\rho - r) \right],$$

where $\bar{g}$ is the amount of money that B lends out.

Agent A can be thought of as a cash-rich investor, such as a MMF, that does not face regulatory constraints. This agent can only lend to agent B ($\bar{a} = 0$), invests in the risky and risk-free asset, and lends its remaining wealth to other agents (or invests in the risk-free asset) at the broad lending rate r. Agent B is a bank that faces regulatory constraints and can borrow money from A at the rate r. B's regulatory constraint limits its risky investments and capacity to lend out money, the constraint can be thought of as leverage ratio constraint:

$$\frac{W^B}{b+\bar{b}} \geq x,$$

where W^B can be interpreted as the banks' capital, $b+\bar{b}$ as the total exposure and x as a fixed number between 3% and 6%. We restrict the model parameters such that we end up in the realistic case where A and B take long positions in the risky asset and assume that there is a fixed demand $\bar{c}$ for cash by another agent (which could be another bank or a non-bank). The following proposition illustrates how r and ρ are affected by tighter regulatory constraints.

Let $\Omega = W^A + W^B$ and $\mathcal{B} = \frac{\frac{1}{x}W^B}{\Omega - \S + \bar{b}}$.

(a) If $\mathcal{B} \geq \frac{1}{2}$, the bank is unconstrained and $r = \rho = \mu - \frac{\gamma\sigma^2}{2}(\Omega - \mathcal{S} - \bar{b})$

(b) If $\mathcal{B} < \frac{1}{2}$, the bank is constrained and

$$r = \mu - \gamma\sigma^2[(1-\mathcal{B})(\Omega - \mathcal{S}) - \mathcal{B}\bar{b}]$$
$$\rho = \mu - \gamma\sigma^2[\mathcal{B}(\Omega - \mathcal{S}) + (1+\mathcal{B})\bar{b}]$$

We relegate the proof of Proposition 5.B to the internet appendix and focus on the economic intuition behind the proposition instead. The variable $\mathcal{B}$ can be interpreted as tightness of the bank's constraint, i.e. a lower $\mathcal{B}$ implies that the bank is more constrained. Focusing on part (b), the proposition shows that tighter constraints, reflected by a lower $\mathcal{B}$, decreases r but increases ρ. Hence, the proposition illustrates how a binding LR constraint affects interest rates differently, depending on whether the marginal lender is an unconstrained non-bank or a constrained bank.

Internet Appendix

(Not for publication)

5.A Data Description

1. *Alternative benchmark rates:* We obtain backward-calculated (for the April 2014 – May 2018) and actual (from May 2018 on) SOFR rates from the New York Fed website. Data for the SONIA and reformed SONIA rate come from the BoE. ESTR and pre-ESTR rates are obtained from the ECB website.

2. *Libor and Euribor rates:* We obtain 3-month term and overnightfor USD and GBP , as well as 3-month EURIBOR and EONIA (as a measure of overnight EURIBOR) rates from the Bloomberg system.

3. *Key policy rates:* For the U.S., we use the IOER rate, for the U.K., we use the "bank rate", and for Europe, we use the bank deposit rates. All three rates are obtained from Bloomberg.

4. *Government debt outstanding:* We use auction data from `TreasuryDirect.com`, the U.K. debt management office, and the German finance ministry to construct the daily volume of U.S., U.K., and German Treasury debt outstanding, respectively.

5. *Transaction volumes:* We obtain SOFR volumes, split into tri-party, GCF, and bilateral transactions from the New York Fed website. SONIA volumes come from the BoE. ESTR volumes are obtained from the ECB website.

6. *Reserves:* For the U.S., we use the total balances with Federal reserve banks; For the U.K., we use excess reserves at BoE deposit accounts; For Europe, we use excess reserves defined as deposits at the deposit account net recourse to the marginal lending facility. All three quantities are obtained from the Bloomberg system

7. *Primary dealer net repo:* To construct primary dealers' net repo positions, we obtain the volume of overnight repo and reverse repo positions against Treasury collateral from the New York Fed website.

8. *Fed security holdings:* We obtain the total assets on Fed's balance sheet and the quantity of Treasury securities held by the Fed from FRED.

9. *Additional U.S. rates:* Additional GCF repo data come from the DTCC website and tri-party repo data from BNY Mellon. The EFFR is obtained from FRED.

10. *Euro-dollar futures:* Euro-dollar futures are futures contracts that allow investors to take positions on the 3-month LIBOR rate at a future point in time. Prices and open interest for Euro-dollar futures are obtained from the Bloomberg system.

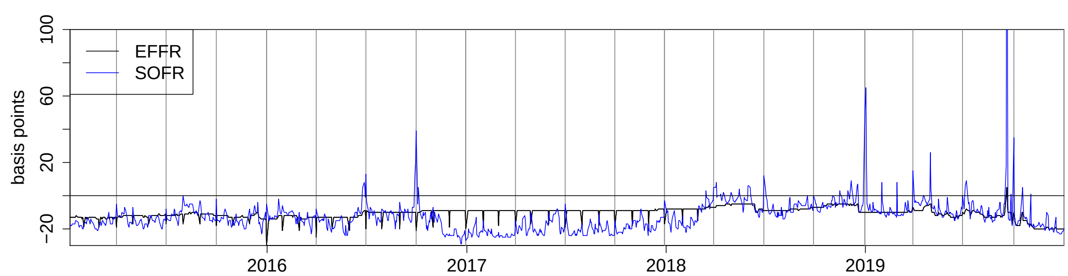
11. *Fed funds futures:* Fed funds futures are futures contracts that allow investors to take positions on the average EFFR in a given month. Prices and open interest for Fed funds futures are obtained from the Bloomberg system.

12. *SOFR futures:* SOFR futures rates for 1-month futures (which resemble Fed funds futures) and 3-month futures (which resemble Euro-dollar futures) prices and open interest are obtained from the Bloomberg system.

5.B Additional Details on the EFFR

The EFFR is the benchmark rate in more than $20 trillion overnight index swaps (OIS) and one aim of U.S. monetary policy is to keep the EFFR within a target corridor. Figure 5.B.1 compares the EFFR to SOFR. As we can see from the figure, the EFFR is relatively stable and tends to spike downward on quarter-ends and month-ends (although these downward spikes have diminished in early 2018).

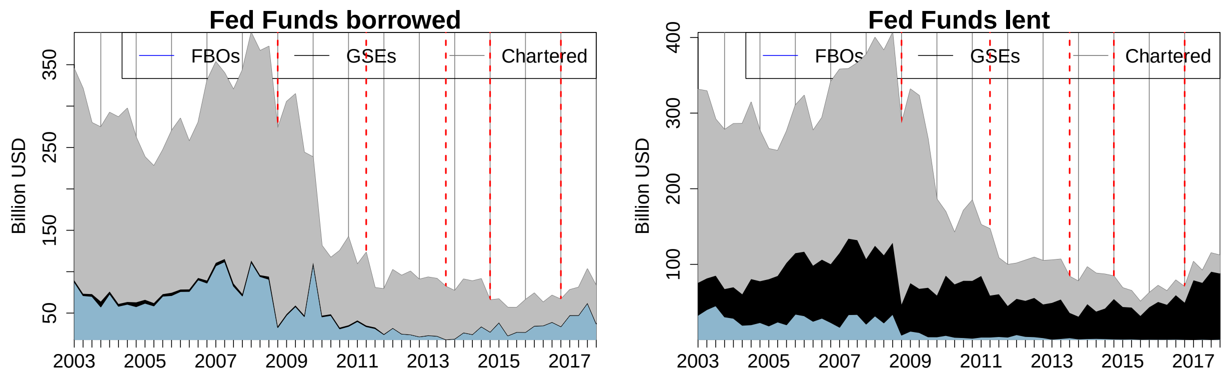
Figure 5.B.1
Comparison of SOFR and EFFR



Notes: This figure compares the level of SOFR (blue line) the EFFR. To remove the effect of changes in policy target rates, each line represents the spread between the respective rate and IOER. The grey vertical lines indicate quarter-ends.

The main lenders in the Fed Funds market are Government Sponsored Entities (GSEs), which face less stringent regulatory requirements compared to banks and can be thought of as non-bank lenders in our framework (transaction type T1). Figure 5.B.2 illustrates the volumes in the Fed funds market over time and confirms that GSEs became the predominant lender after the financial crisis. Note that, prior to the financial crisis, the Fed Funds market was an important venue for banks to trade excess reserves. However, the increasing amount of excess reserves in the banking sector (which was a consequence of unconventional monetary policy) prompted the Fed to start paying interest on excess reserves (IOER) in December 2008, thereby lowering banks' incentives to lend their excess reserves to other banks. Figure 5.B.2 shows that the major borrowers in the Fed Funds market are foreign banking offices (FBOs), which unlike domestic banks, do not pay a balance-sheet fee to the Federal Deposit Insurance Corporation and are responsible for 45% of the borrowing.

Figure 5.B.2
Fed Funds volumes by counterparty



Notes: This figure shows quarterly fed funds volumes, split by counterparty. The dashed vertical lines correspond to the quarters when IOER was introduced (Q4 2008), the FDIC reform (Q2 2011), the introduction of the RRP facility (Q3 2013), the public disclosure of the leverage ratio (Q1 2015), and the implementation of the MMF reform (Q4 2016). The source of these data are the financial accounts of the U.S. Chartered bank borrowing and lending in the fed funds market became only available in January 2012 and we use the amount of interbank lending by chartered depository instituions as a proxy before that date. To keep the exposition clear, we drop credit unions, which only have fed funds different from zero in four quarters.

5.C The Impact of Regulation

We now compare the impact of the introduction of leverage ratio reporting on different collateralized and uncollateralized overnight rates in the U.S., the U.K. and Europe. As for the U.S. before, we regress the spread between overnight rate and policy target rate on QEnd, YEnd, and MEnd \ QEnd, testing if the dummy variable became more significant after January 2013. Because SOFR, the reformed SONIA rate, and ESTR are not available before 2013, we use the GCF repo rate, SONIA, EONIA as well as the EFFR and overnight repo rates backed with U.K. gilts or German Treasuries as collateral. Focusing first on the U.S., Panels (1) and (2) of Table 5.C.1 show that month-end downward spikes in the EFFR and quarter-end upward spikes in GCF repo rates started appearing after 2013. Given that GCF repo can be viewed as interbank transactions while the EFFR corresponds more to transactions of type *T1*, this finding supports Hypothesis 1.

Turning to the U.K., Panels (3) and (4) show that quarter-end and month-end spikes became more pronounced post-2013 and that the spikes ar more pronounced for repo rates compared to the uncollateralized SONIA rate. Focusing next on the Euro area, Panels (5) and (6) show that EONIA exhibits significant upward spikes at quarter-ends but not at month-ends. By contrast, the repo rate based on German collateral shows significant downward spikes at quarter-ends in the post-2013 period, which were upward spikes in the 2010 – 2013 period. In line with the LR being reported based on quarter-end snapshots in Europe, month-end spikes are insignificant for both EONIA and repo. However, the large quarter-end spikes in EONIA did not become more significant after 2013. This is most likely due to the impact of the European debt crisis on unsecured overnight rates in Europe, which increased volatility in the rate.

Table 5.C.1
Changing reporting-date spikes in different overnight rates

	EFFR (1)	GCF (2)	SONIA (3)	Repo UK (4)	EONIA (5)	Repo DE (6)
QEnd	-4.79^{***}	0.94	3.42	-0.41	23.59^{***}	10.75^{***}
	(-5.66)	(0.39)	(1.32)	(-0.32)	(3.14)	(3.05)
YEnd	1.26	-4.43	-5.89^{*}	-10.15	-24.62^{**}	-29.31^{***}
	(0.66)	(-1.12)	(-1.80)	(-1.52)	(-2.24)	(-3.92)
MEnd \ QEnd	0.36	3.93^{***}	0.38	-1.59^{***}	3.41	1.00
	(1.37)	(4.29)	(1.64)	(-2.80)	(1.07)	(0.44)
QEnd × $1_{\{\geq 2013\}}$	0.39	18.61^{***}	-6.79^{**}	-10.55^{***}	-15.66^{*}	-23.85^{***}
	(0.30)	(3.91)	(-2.54)	(-4.18)	(-1.95)	(-3.17)
YEnd × $1_{\{\geq 2013\}}$	-3.52	29.23	3.27	-28.19^{*}	25.94^{**}	-68.04
	(-1.23)	(0.85)	(0.87)	(-1.65)	(2.14)	(-1.33)
MEnd \ QEnd × $1_{\{\geq 2013\}}$	-3.54^{***}	2.03	-1.19^{***}	-5.47^{***}	0.46	1.50
	(-4.60)	(1.44)	(-4.54)	(-4.67)	(0.14)	(0.63)
Adj. R^2	0.70	0.33	0.91	0.62	0.68	0.71
Num. obs.	2,543	2,475	2,518	2,518	2,555	2,555

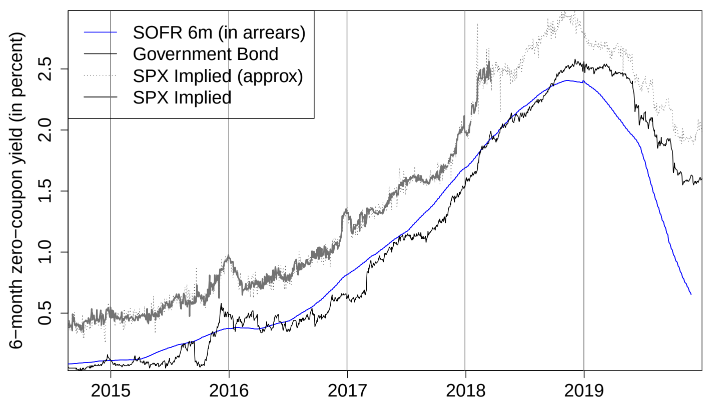
Notes: This table shows the results of regressing the spread between the indicated overnight rate and key policy rate for the respective area on several dummy variables. QEnd and YEnd are dummy variables that equal one on the last trading day of a quarter or year and zero otherwise. MEnd \ QEnd is a dummy variable that equals one on the last day of a month if that day is not the last day of a quarter, and zero otherwise. $1_{\geq 2013}$ is a dummy variable that equals one if the obseration is after January 2013 and zero otherwise. All specifications include year-quarter fixed effects. The sample period is is January 2010 to December 2019. The numbers in parantheses are Newey-West t-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively.

5.D Additional Descriptive Statistics

This section contains three additional descriptive statistics. Figure 5.D.1 compares the 6-month SOFR average, computed in arrears, to the option-implied risk-free rate estimated by Van Binsbergen et al. (2019).

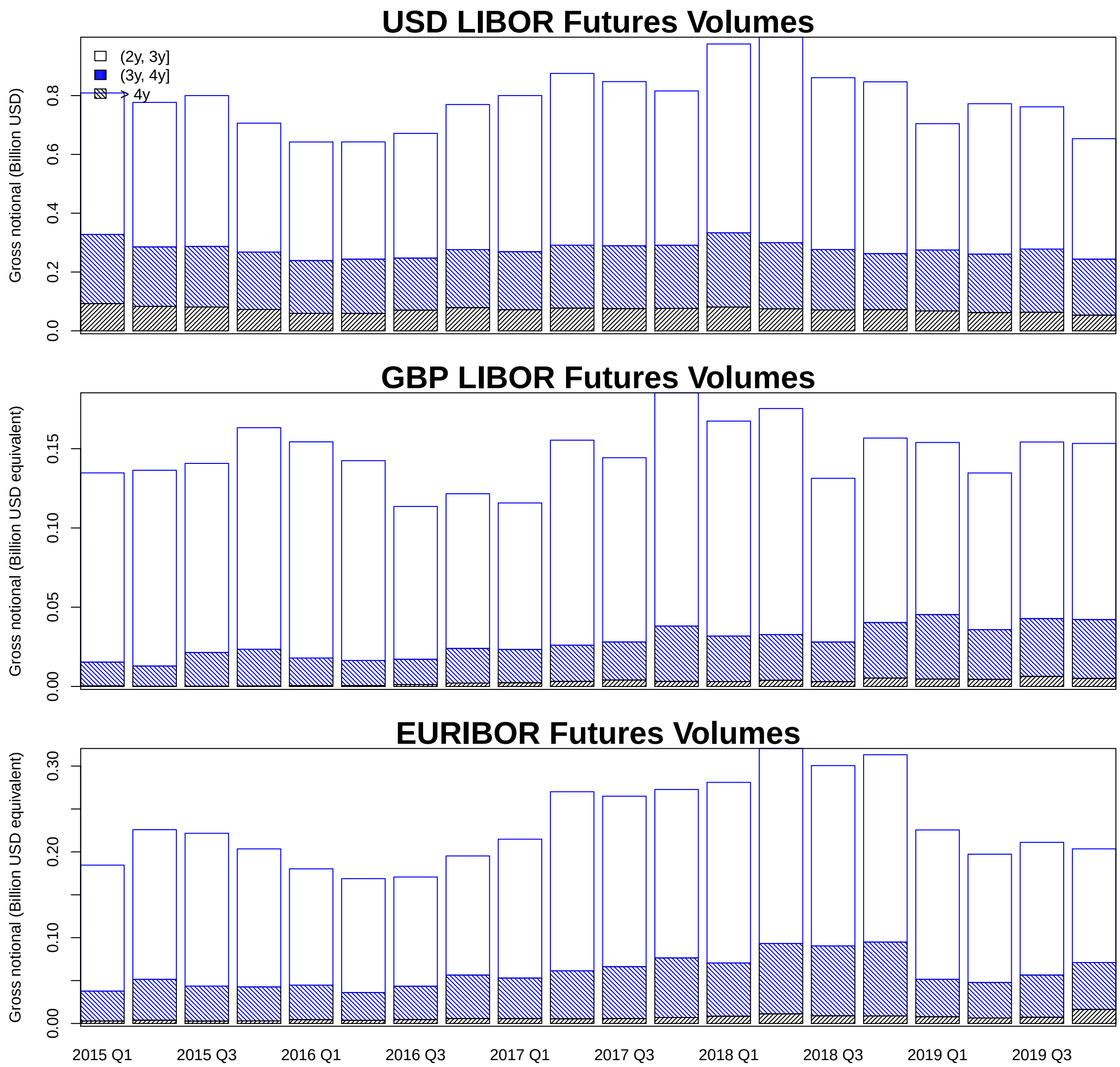
Figure 5.D.2 shows the average open interest in Euro-dollar futures, averaged from one expiry date to the next, split into three maturity buckets: greater than 2 year, but less than 3 years; greater than 3 years but less than 4 years; and greater than 4 years. Figure 5.D.3 compares monthly gross notional of interest rate derivatives reported to DTCC split into contracts referencing and contracts referencing SOFR.

Figure 5.D.1
Comparison between term SOFR and other risk-free rate proxies



Notes: This figure compares 6-month term SOFR (computed in arrears) to 6-monht constant maturity Treasury yields and the option-implied risk-free rate estimated in Van Binsbergen et. al (2019), as well as an estimate of the option-implied rate using end-of-day option prices.

Figure 5.D.2
Open interest in Euro-dollar futures



Notes: This figure shows quarterly average open interest in euro-dollar futures, sampled between IMM dates, The Euro-dollar futures reference either USD , GBP , or Euribor. Volumes are split into three different maturity buckets: Maturity between 2 and 3 years $(2y, 3y]$, maturity between 3 and 4 years $(3y, 4y]$, and maturity greater than 4 years.

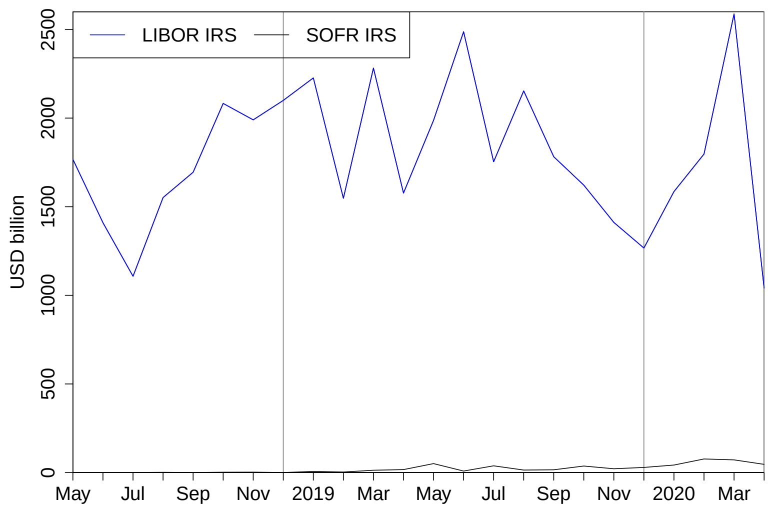


Figure 5.D.3
Interest rate swap volumes

Notes: This figure shows monthly gross trading volumes of interest rate swaps with LIBOR as underlying (blue line) and SOFR as underlying (black line). The transactions are obtained from the DTCC trade repository.

5.E Proof of Proposition 1

To prove Proposition 1, we proceed in three steps. First, we determine the agents' optimal investments as functions of the rates r and ρ. Second, we use these optimal investments to derive expressions for r and ρ, conditional on agent B either being constrained or unconstrained. Finally, we determine the region in which agent B is constrained.

First, we start by determining A's optimal investment in the risky asset, which is the solution to a standard mean-variance optimization problem and given as:

$$a = \frac{\mu - r}{\gamma \sigma^2}, \tag{5.3}$$

assuming a sufficiently large W^A. The remaining amount $W^A - a$ needs to be invested in risk-free assets. Subtracting the amount of outstanding Treasuries § gives the total amount that A is lending to B:

$$W^A - a - \S. \tag{5.4}$$

The bank's optimization problem is given as:

$$\max_{b,\bar{b}} \left[b(\mu - r - \gamma b\frac{\sigma^2}{2}) + \bar{b}(\rho - r) \right]$$
$$\text{s.t. } b + \bar{b} \leq \frac{1}{x} W^B,$$

where we assume that both b and $\bar{b}$ are positive (i.e. long positions in the risky asset and lending money to other banks). B's Lagrangian is given as:

$$\mathcal{L}(b, \bar{b}, \lambda) = b\left(\mu - r - \gamma b\frac{\sigma^2}{2}\right) + \bar{b}(\rho - r) - \lambda(xb + x\bar{b} - W^B)$$

and taking the first-order condition (FOC) gives:

$$\frac{\partial \mathcal{L}}{\partial b} : \mu - r - \gamma b\sigma^2 - \lambda = 0 \Leftrightarrow b = \frac{\mu - r}{\gamma\sigma^2} - \frac{\lambda}{\gamma\sigma^2}$$
$$\frac{\partial \mathcal{L}}{\partial \bar{b}} : \rho - r - \lambda = 0 \Leftrightarrow \lambda = \rho - r$$

If B is unconstrained, we have $\lambda = 0$ and hence $\rho = r$ and $b = a$. If B is constrained, plugging λ in gives the following investment in the risky asset:

$$b = \frac{\mu - \rho}{\gamma\sigma^2}.$$

In addition, if B is constrained, we know that $b + \bar{b} = \frac{1}{x}W^B$ and hence

$$\bar{b} = \frac{1}{x}W^B - b.$$

Second, to determine r, we assume market clearing in the non-bank to bank lending market, which implies:

$$(W^B - b - \bar{b}) + (W^A - a - \mathcal{S}) \overset{!}{=} 0. \tag{5.5}$$

Depending on whether B is unconstrained or constrained, solving Equation (5.5) for r gives:

$$r = \begin{cases} \mu - \frac{\gamma\sigma^2}{2}[(W^A - \S) + W^B - \bar{b}], \text{ if } B \text{ is unconstrained} \\ 2\left[\mu - \frac{\gamma\sigma^2}{2}((W^A - \S) + W^B - \bar{b})\right] - \rho, \text{ if } B \text{ is constrained.} \end{cases} \tag{5.6}$$

To determine ρ, we assume market clearing for bank lending:

$$\left(\frac{1}{x}W^B - b\right) + \bar{c} \overset{!}{=} 0. \tag{5.7}$$

Because we already know that B being uncostrained implies that $\rho = r$, we focus on the case where B is constrained and solving Equation (5.7) for ρ leads to:

$$\rho = \mu - \gamma\sigma^2 \left(\frac{1}{x}W^B + \bar{c}\right). \tag{5.8}$$

Plugging ρ into the constrained case in Equation (5.6) gives:

$$r = \mu - \gamma\sigma^2 \left[(W^A - \S) - \left(\frac{1}{x} - 1\right) W^B\right], \text{ if } B \text{ is constrained.} \tag{5.9}$$

Third, B is unconstrained if $\frac{\mu - r}{\gamma\sigma^2} + \bar{b} < \frac{1}{x}W^B$, which is the case if:

$$\frac{\frac{1}{x}W^B}{W^A + W^B - \S + \bar{b}} < 1/2.$$

Replacing $-\bar{c}$ with $\bar{b}$ and rewriting the expressions in terms of $\mathcal{B}$ completes the proof. ■

Chapter 6

Does Publication of Interest Rate Paths Provide Guidance?*

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6.1 Introduction

The practice of publicly communicating future policy intentions, forward guidance, is by now widespread among central banks. Communication strategies take different forms, from loosely indicating future policy options through speeches, to the more explicit form of describing the central bank's planned conditional course of action through published interest rate projections (IRPs). The latter form has now been pursued by New Zealand, Norway and Sweden for more than a decade.

As a conceptual simplification, we find it useful to distinguish between two main motives for this development.[1] First, by announcing a plan for future policy rates the central bank might directly affect long-term interest rates. Communication can then be justified as a means to control more than just short-term rates, a rationale that is particularly relevant close to the zero-lower bound. Second, statements about future plans, coupled with explanations of the considerations behind them, may serve to improve market participants' understanding of the central bank's systematic reaction pattern. Here communication is motivated as a means to sharpen the effectiveness of monetary policy's systematic component by improving market participants' ability to map current information into likely monetary policy consequences. The following statement by Ben Bernanke, then Chairman of the Board of Governors of the Federal Reserve System, is illustrative of this second motivation: "I believed then, as I do today, that transparency enhances public understanding [. . .] and ultimately makes policy more effective by tightening the linkage between monetary policy, financial conditions, and the real economy" (Bernanke, 2013).

The trend toward more explicit policy communication by central banks has been followed by careful empirical studies to analyze its consequences. This literature has largely been oriented toward the first of the two motives above, and has documented that central bank communication actually does affect market rates. However, little is known about the extent to which communication serves its second rationale; to improve markets' understanding of the central bank's reaction pattern. In this paper, we are more oriented toward this second motivation, as we explore how the practice of publishing interest rate projections (IRPs) has influenced market participants' ability to forecast interest rates.

Our empirical strategy is to study market interest rate reactions in tight windows around monetary policy announcements and other macroeconomic releases in Norway and Sweden. These two countries are particularly well suited for our purposes since they introduced IRPs within otherwise stable monetary policy regimes of inflation targeting. Moreover, with a difference-in-differences approach, we contrast market reactions in Norway and Sweden, which began to publish IRPs in 2005 and 2007 respectively, to market reactions in New Zealand and Canada which both have targeted inflation over our sample period, but have not introduced IRPs in this time frame.[2]

[1]In practice these two motives are closely connected and likely to be simultaneously at play, but for the purpose of disseminating and evaluating the rationale behind policy communication, we believe the distinction is useful. Blinder et al. (2008) articulate a similar distinction, separating between "creating news" and "reducing noise".

[2]New Zealand has published IRPs throughout our sample period, Canada has yet not introduced IRPs. Note that we cannot focus on New Zealand alone, because we lack high-frequency data before it introduced IRPs in 1997, and

Our starting point is to back out market expectations of future 3-month interest rates from forward rate agreements (FRAs). We next compute the markets' forecast errors (MFEs) at four different horizons up to one year ahead, by comparing these expectations to the actual realizations of each respective 3-month interest rate. Following earlier literature, we study if markets reacted to announcements of monetary policy and various macroeconomic releases, but we also move one step further and ask if the reactions were in the right direction: did the announcements serve to improve market participants' ability to forecast future monetary policy?

To fix ideas, we anticipate our analysis and display in Figure 6.1 how MFEs have responded to a variety of announcements. The graphs show two-year rolling regressions estimates, together with two standard deviation error bands, of the impact of macroeconomic releases and monetary policy announcements, on MFE-changes occurring within 30-minute windows around each announcement.[4] Overall, monetary policy announcements and macroeconomic releases tend to reduce MFEs and hence move market interest rate expectations toward ex-post realizations. The vertical lines in Figure 6.1 mark the introduction of IRPs. Our question is if communication of future policy intentions through IRPs stimulated this tendency toward MFE reductions.

[Insert Figure 6.1 about here]

Figure 6.1 suggests that there might have been improved market reactions in Sweden, but not in Norway. Further analysis provides two perspectives on this difference. First, for other releases than the monetary policy decision, such as the monthly updates on consumer price inflation, there is no sign in either country that the presence of IRPs improved market reactions. The improvements in Sweden are present only for responses to monetary policy announcements.

Second, whenever monetary policy announcements have reduced MFEs in either Norway or Sweden, this has occurred via market reactions to implemented policy actions, not via reactions to communication of future policy intentions. We reach this conclusion after using the approach of Gürkaynak et al. (2005) to distinguish market reactions to implemented policy from communication of future policy intentions. This method, by now the workhorse for empirical work on forward guidance, decomposes market reactions to monetary policy announcements into a target and a path factor. The former captures movements in the current short-term interest rate level, while the latter captures longer-term interest rate movements that are orthogonal to the short-term rate. Hence, the target factor can be interpreted as the market response to monetary policy actions, while the path factor can be interpreted as responses to communication of future intentions that cannot be inferred from implemented policy. In the Norwegian and Swedish data, one observes substantial reactions through both the path and target factor when monetary policy decisions are announced.

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because its policy regime changed after IRPs were introduced.

[4]The estimates are obtained by pooling all releases as in Swanson and Williams (2014), and each estimate is centered on the respective release, using data one year back and one year forward. Further details are provided in the appendix' section 6.B.

Strikingly though, the path-reactions do *not* generally serve to reduce forecast errors, neither before nor after IRPs were introduced in either country. Hence, communication of future policy intentions that cannot be inferred from current actions alone, have not served to reduce forecast errors. The practice of publishing IRPs has not changed this pattern.

The common finding across time and our two countries, is that when monetary policy announcements have reduced MFEs, this has occurred via the target factor only. In Norway this occurred already before interest rate projections were utilized, and the strength with which target reactions reduced forecast errors did not change after interest rate projections were introduced. In Sweden, in contrast, this effect is only present after the Riksbank began to publish interest rate projections, not before. It thus seems that it is the two central banks' *actions* that has mattered for markets' forecast errors. Regarding why the target factor began to reduce forecast errors in Sweden after they introduced IRPs, we can only speculate. A plausible explanation might be that in Sweden, the introduction of IRPs in 2007 improved the central bank's explanations of its current policy actions. In Norway, the current actions gave reduced forecast errors already before IRPs came into use, which might be why the introduction of IRPs in 2005 did not improve markets' understanding of policy actions any further. Arguably, explanation of current actions does not require the publication of future policy intentions.

Our use of high-frequency interest rate futures data to capture market expectations about monetary policy dates back to Guthrie and Wright (2000) and Kuttner (2001). Gürkaynak et al. (2005) followed in their footsteps when decomposing market reactions into target and path factors. They found that both actions and statements influence asset prices, and particularly that statements have greater influence on long-term Treasury yields. Campbell et al. (2012) have later utilized this same decomposition, finding similar effects of FOMC statements right up until and well into the financial crisis, concluding that statements can influence market rates even when one is close to or at the zero-lower-bound. They also argue that these reactions are driven by perceptions that the central bank has superior knowledge about the underlying state of the economy, rather than that statements commit policymakers to a future course of action.

In a related paper, Brubakk et al. (2017) have recently approached the Norwegian and Swedish data in similar spirit, asking if the path factor shifts when the two countries' central banks announce new interest rate projections. Brand et al. (2010) and Leombroni et al. (2017) distinguish communication from actions more directly, by separating market reactions to ECBs publication of current policy decisions from market reactions to ECBs press conference 45 minutes later. All these studies find considerable reactions to communication.[5]

While our paper shares the above literature's focus on high-frequent market reactions, our analysis differs by asking if policy communication guides markets to *improved* interpretation of available information, rather than just asking if communication *shifts* market rates.

[5]A full survey of the literature on how central bank communication affects interest rates is beyond the scope of this paper. For an early summary of studies in the field, tending to find that communication affects interest rates, see Blinder et al. (2008).

Our focus on market participants' ability to predict future policy rates is shared by Kool and Thornton (2015). They use survey forecasts and evaluate if these forecast were improved after forward guidance was introduced, finding moderately improved forecastability over short horizons in Norway and Sweden. We use high-frequency traded FRAs, rather than infrequent survey data, to measure market expectations. Not only do the FRAs reliably capture market expectations because they are actually traded upon, but their high frequency allows us to credibly estimate how market expectations react to released information. Beechey and Österholm (2014) also use expectations inferred from market data. They evaluate the forecasting properties of central bank IRPs and market participants' forecasts at the same time, and find that they share similar properties of biasedness, (in-)efficiency and low forecast precision.

The theoretical literature on forward guidance provides ample motivation for our study. Woodford (2001) discusses general advantages of having the central bank communicate its policy intentions, arguing that transparency is key to policy effectiveness. Rudebusch and Williams (2008) argue, within a New Keynesian model with incomplete information, that a central bank that publishes interest rate projections can improve welfare by informing market participants about the central bank's reaction function. The reason is that IRPs guide private agents to better map observed macroeconomic events into future interest rate consequences. On the other hand, Morris and Shin (2002) formalize the concern that central bank communication might prevent private agents from utilizing other sources of information, which brings even the theoretical benefits of IRP publication into question.[7]

Overall, our results indicate that the practice of publishing interest rate projections has not improved markets' understanding of what new macroeconomic information implies for future interest rates. However, our findings do not support the Morris and Shin hypothesis either, as market forecasts have continued to be improved by macroeconomic releases to approximately the same extent after IRPs became available, as before. Hence, we do not contend that the publication of interest rate projections has distorted markets. Rather, our evidence more neutrally establishes that so far, the observed communication of future policy intentions through IRPs has not guided markets to better anticipate how interest rates will be set in the future.

In what follows, Section 6.2 describes our data and the institutional settings behind them. In Section 6.3 we study market reactions to monetary policy announcements, while in Section 6.4 we consider macroeconomic releases. Section 6.5 concludes.

[7]Svensson (2006) show that this result is overturned if the central bank has somewhat precise information.

6.2 Interest Rates and Monetary Policy in Norway, Sweden, New Zealand, and Canada

We will study the role of central bank forecasts in Norway and Sweden, using New Zealand and Canada as controls in an extension. These countries are all (relatively) small open economies, which have been under an inflation targeting monetary policy regime over our entire sample period, spanning January 2000 throughout March 2019.

6.2.1 Institutional Setting

Norges Bank began to publish its own forecast for the key policy rate (the sight deposit rate) on November 2, 2005, while Sveriges Riksbank followed by publishing its own IRP for their key policy rate (the repo rate) on February 15, 2007. Forecast horizons have varied somewhat, typically between 12 and 15 quarters for Norges Bank and up to three years for the Riksbank.

In both Norway and Sweden, the policy rate forecasts are conditional on macroeconomic projections based on economic models together with judgment by the Monetary Policy Committee, and published in Monetary Policy Reports following an interest rate decision. The forecasts are for quarterly averages of the key policy rate. Over our sample period, both countries have primarily emphasized inflation and output gaps as their main target variables, but they increasingly emphasized financial stability toward the end of our sample.

A key difference between the two institutions is that the Riksbank has accompanied every policy rate announcement with an updated IRP, while Norges Bank publish their IRP somewhat less frequently. Currently, the Riksbank decides on its policy rate six times a year, but this frequency has varied up to eight per year in our sample period. Until 2013, Norges Bank published interest rate projections three times per year, usually in March, June and October. Since 2013 Norges Bank has published its IRP four times a year, while it makes 6 interest rate decisions per year. Over our sample period, the frequency of Norges Bank's interest rate decisions has varied from six to ten per year. Both the Riksbank and Norges Bank publish confidence bands together with their point forecasts.[8]

The Reserve Bank of New Zealand (RBNZ) began publishing its own IRPs in 1997. The forecast horizon is 8 quarters, and the interest rate being forecast is the quarterly average of the 90-day Bank Bill rate. RBNZ's procedure for publishing is very similar to that in Norway and Sweden, see Mirkov and Natvik (2016) or Drew and Karagedikli (2008) for further details. The Bank of Canada has not pursued a policy of publishing IRPs in our sample period, but did for a period in 2009-2010 utilize other explicit means of forward guidance, see Charbonneau and Rennison (2015).

[8]For further details on monetary policy and interest rate projections in Norway and Sweden, see Holmsen et al. (2008) and Riksbank (2017) respectively.

6.2.2 Data

We use high-frequency data on forward rate agreements (FRAs) for Norway, Sweden, and New Zealand, provided by the Thomson Reuters Tick History database, as our measure for market expectations. Our sample period is 01.01.2000 to 03.31.2019. The FRA contracts are comparable to the US Libor future contracts traded on CME. For Canada we use such interest rate futures. For all countries the horizons are fixed at the International Money Market (IMM) dates.[9]

Let $i_{t,h}^{market}$ denote the FRA-rate for the future 3-month interbank interest rate at IMM-horizon h, determined in the market at time t. We want to measure the forecast error for the ex-post realization of the 3-month rate at the same date as the horizon h, and denote this rate $i_{\tau(h)}$, where $\tau(h)$ denotes the IMM-date for horizon h. We let mfe_t^h denote the market forecast error implied by a forward rate at time t for horizon h. Hence, MFEs are defined as follows:

$$mfe_t^h = i_{\tau(h)} - i_{t,h}^{market}. \tag{6.1}$$

We will consider the first four IMM-dates as forecast horizons h, each approximately one quarter ahead following time t.

The interest rate $i_{t,h}^{market}$ is directly quoted by market participants at high frequency. We will utilize the change in mfe_t^h within narrow windows around announced interest rate decisions or released updates on key macroeconomic variables. For this purpose, we collect the exact timing of both macro releases and monetary policy announcements in Norway, Sweden, New Zealand, and Canada. The window we will use is from immediately before the new information is available to market participants, to 30 minutes after.

The benefit of a rather narrow window, is that confounding factors that affect interest rates are less problematic. The narrower the window, the more likely we are to isolate the effect of each specific information event. On the other hand, if markets need time to react, a wider window may be necessary to capture their response. Figure 6.2 presents market reactions at different intervals after monetary policy announcements. We see that most of the reaction typically occurs in the first 15 minutes, but between 15 and 30 minutes after announcements there will often still be marked movements. There is a clear tendency for the forward rates to settle down thereafter, as we see the response from 30 to 45 minutes after announcements are negligible.[11]

[Insert Figure 6.2 about here]

We consider releases of the following macroeconomic variables: The consumer price index (monthly), industrial production (monthly), the trade balance (monthly), gross domestic product (quarterly),

[9] IMM dates are the quarterly dates which most futures contracts and option contracts use as their scheduled maturity date or termination date. The IMM dates are the third Wednesday in March, June, September and December.

[11] For brevity, Figure 6.2 displays only movements in the FRA maturing four IMM dates ahead. The patterns for shorter horizons are similar. Results available upon request.

PMI headline (purchasing managers sentiment index, monthly), retail sales (monthly), the unemployment rate (monthly), the economic tendency indicator (Sweden only, monthly), oil investments (Norway only, quarterly), a credit aggregate (Norway only, monthly).

The IRPs in Norway and Sweden provide the central banks' forecasts of future (short-term) *policy* rates. In contrast, FRAs capture the markets' forecasts of future (short-term) *market* rates plus an additional term premium. The realized market rates can in turn be considered as the sum of the policy rate plus a short-term premium. This raises two notable issues with our empirical approach.

First, our object of interest, mfe_t^h, regards market rates only: We will compare FRAs to realized market rates. Strictly speaking, this means that we are estimating how new information affects markets' ability to forecast future market rates, not future policy rates alone. These responses will reflect the markets' ability to forecast policy rates under the additional assumption that our observed short-window changes in FRAs reflect changes in expectations about policy rates, not changes in expected short-term premia.

Second, the fact that FRAs might reflect term premia in addition to expected future market rates means that it is simplistic to consider the level of mfe_t^h as a forecast error only. This is why our interest lies in high-frequent MFE *changes* rather than levels. We will study MFE changes in 30-minute windows around releases of monetary policy decisions and other macroeconomic news, and then interpret these responses as movements in forecast errors under the assumption that FRA premia are constant in these specific windows. This assumption is typically imposed in the empirical literature on monetary policy communication, see for instance Gürkaynak (2005) and Brand et al. (2010).

While it is common practice in the literature to assume that premia are constant around announcements and macroeconomic releases, we acknowledge that it is impossible to validate this assumption with certainty. Generally speaking, variation in term premia within the narrow windows we study would work against detecting statistical evidence that markets' forecast errors respond. We therefore anticipate our results and note that MFEs generally do fall in our announcement windows. Hence, it seems unlikely that the FRA-variation our empirical strategy utilizes is driven by premia alone. Moreover, we will find a different impact of IRP introduction on MFE responses in Norway than in Sweden. If these differences are driven by premia alone, then term premia variability must be correlated with the introduction of IRPs in one country, but not in the other. This also seems unlikely. We therefore believe the assumption of constant premia is innocuous. Moreover, in the conclusion we return to how one of our results may be re-interpreted if both premia and expectations are responding.

6.3 How Do Monetary Policy Announcements Affect Market Forecast Errors?

The extent to which a monetary policy announcement guides markets about the future evolution of short-term interest rates will be reflected in how mfe_t^h responds. Note that it is the absolute value of forecast errors that matters here: we need not distinguish between an initially negative forecast error that moves up or an initially positive forecast error that moves down,- in both cases the forecast moves closer to the ex-post realization. Hence, we will study movements in market forecast errors from right before an announcement to 30 minutes after, defined as $\Delta|mfe_t^h| = |mfe_t^h|^{+30min} - |mfe_t^h|^{\div Ann}$.

First, we assess if the response of $\Delta|mfe_t^h|$ to monetary policy announcements changed after Norges Bank and the Riksbank began to publish IRPs. Second, we ask if the underlying drivers behind the patterns observed are market responses to current monetary policy actions or market responses to communicated monetary policy intentions that cannot be inferred from policy actions.

6.3.1 MFE Responses and interest rate projections

Figures 6.3 and 6.4 plot the change in market forecast errors, $\Delta|mfe_t^h|$, around monetary policy announcements in Norway and Sweden. Each figure contains one plot per horizon h. Red circles refer to announcements which were accompanied by the central bank's IRP, blue circles refer to announcements that were unaccompanied by an IRP. The high number of positive values reveals that a monetary policy announcement does not necessarily contribute to a reduced forecast error. Naive eyeballing of the movements in forecast errors leaves the impression of no particular pattern other than a mean response close to zero.

[Insert Figures 6.3 and 6.4 about here]

The blue solid lines in each figure display the average MFE response to announcements that are unaccompanied by IRPs. In Norway this line lies below zero, implying that interest rate announcements without IRPs on average have guided markets toward the realized future interest rate level. The red line shows the mean MFE responses to announcements accompanied by IRPs. We see that for Norway the red and blue lines lie close to each other, indicating that the publication of IRPs have not added information above the ordinary interest rate announcements. In Sweden, shown in Figure 6.4, on the other hand, the red line lies below the blue line at all horizons. This indicates that monetary policy announcements have been more informative after the Riksbank began to publish its own interest rate projection.

An alternative view of the data is offered by Figure 6.5, which shows kernel estimates of the $\Delta|mfe_t^h|$-distributions around monetary policy announcements. As one would expect, all the distributions are centered close to zero. The Norwegian distributions are highly similar before and after the central bank begun to publish its own interest rate projections. In contrast, in the Swedish distributions we clearly see that after the Riksbank introduced IRPs, mass moved leftwards, toward MFE-reductions, for three out of four horizons.

[Insert Figure 6.5 about here]

To scrutinize the significance of the differences in Figures 6.3 and 6.4, we run simple regressions comparing $\Delta|mfe_t^h|$ before and after IRPs were introduced. We study each horizon in Norway and Sweden separately, starting from the specification

$$\Delta|mfe_t^h| \quad = \quad \psi + \beta I_t + \varepsilon_t, \tag{6.2}$$

where $I_t = 0$ before IRPs were being published, and $I_t = 1$ thereafter. The estimate of ψ will capture the average MFE-response in the years before IRPs were used, while β captures how the average MFE-response has changed thereafter. If the presence of IRPs has provided substantial guidance, β should be negative.

For Norway, we extend this specification to distinguish between policy announcements that were accompanied by a forecast ($D_t = 1$) and meetings that were unaccompanied by a forecast ($D_t = 0$) in the period after IRPs were introduced:

$$\Delta|mfe_t^h| \quad = \quad \psi + \beta_1 I_t D_t + \beta_2 I_t (1 - D_t) + \varepsilon_t. \tag{6.3}$$

For both countries, we also isolate the international financial crises to ensure that results are not driven by anomalies in these particular periods. We provide two alternatives, one for the Global Financial Crisis (GFC) of 2008 and 2009, and another which also includes the Euro-crisis (the dummy runs from 2008 to 2012). In addition, for Sweden we isolate the period 2010-2014 where the Riksbank is claimed to have been "leaning against the wind" by taking house prices into account, without precisely communicating it (Svensson (2015)).[13] For Norway, where we keep the dummy D_t, this implies estimating:

$$\Delta|mfe_t^h| \quad = \quad \psi + \beta_1^{nc} I_t^{nc} D_t + \beta_2^{nc} I_t^{nc} (1 - D_t) + \beta_1^c I_t^c D_t + \beta_2^c I_t^c (1 - D_t) + \varepsilon_t, \tag{6.4}$$

where $I_t^c = 1$ in crisis periods (2008-2009 or 2008-2012), while $I_t^{nc} = 1$ in non-crisis periods after IRPs were introduced. For Sweden, $D_t = 0$ always since almost all meetings have been accompanied by a projection ever since IRPs were first introduced. In addition, for Sweden we have one specification where $I_t^c = 1$ for the leaning period 2010-2014 and $I_t^{nc} = 1$ for the other periods after IRPs were introduced.

[13]In this specification we do not add any of the crisis dummies. We thank an anonymous referee for suggesting that we isolate this specific period.

Results are provided in Tables 6.1 and 6.2 for Norway and Sweden, respectively. For each horizon, the first column refers to the specification in equation (6.2). For Norway, the second column refers to the specification in (6.3). The final two columns refer to specification (6.4) isolating the two alternative definitions of the financial crisis period, 2008-2009 and 2008-2012 respectively.

[Insert Tables 6.1 and 6.2 about here]

The regressions confirm the visual impression from Figures 6.3 and 6.4. Before Norges Bank introduced its projections in 2005, the market forecast errors were on average reduced by monetary policy announcements. The second row shows that the incremental response of $\Delta|mfe_t^h|$ after Norges Bank introduced IRPs in 2005, β from equation (6.2), is positive at all horizons, and statistically insignificant. This holds both for meetings that were accompanied and for meetings that were unaccompanied by an interest rate projection, and is approximately unchanged when we control for crisis periods.

In Sweden, the results go in the opposite direction. MFE-responses were insignificant before the Riksbank introduced its IRPs, and then significantly negative thereafter. When we look at the crisis dummies, it seems that most of the improvements in MFE responses occurred in the crisis periods. However, the sub-period that most clearly stands out is the leaning-against-the-wind period from 2010-2014. In these years the MFE responses are back to their pre-IRP levels. This is consistent with the view that the Riksbank pursued an ill-communicated policy of responding to house prices in this specific period. It seems that the improvements in MFE responses that occurred in Sweden, materialized in the years when the Riksbank was not alleged to pursue an opaquely formulated policy.

The results above indicate that in Sweden, the introduction of IRPs served to guide markets' to interpret policy announcements better, whereas in Norway it did not. However, this interpretation is questionable as the periods before and after IRPs might differ along other important dimensions than the introduction of projections alone. For this reason, we consider a difference-in-differences approach where we compare Norway and Sweden to New Zealand and Canada. In New Zealand, IRPs have been published throughout our sample period. In Canada, the practice of regularly publishing IRPs has not been introduced. Hence, by differencing out the coinciding movements in market forecast errors in New Zealand and Canada, we factor out those sources of time variation that are common across our two countries of interest (Norway and Sweden) and our two control countries (New Zealand and Canada), and unrelated to the introduction of IRPs. Figure 6.A.2 in the appendix shows that the policy interest rates in Norway and Sweden co-move with the policy rates in New Zealand and Canada, supporting the relevance of this exercise.

Because central banks do not hold interest rate meetings on the same days, we need to time-aggregate our data in order to have observations from both countries at the same frequency. Unfortunately for our purposes, there are quarters where some of the central banks in question do not hold policy meetings. We therefore aggregate to the yearly frequency.[15] The aggregated MFE change then is the sum of all MFE changes, as defined earlier over 30-minute windows around monetary policy meetings, during a year. More precisely, the aggregated MFE change for country i in year T is

$$\Delta|MFE^h_{i,T}| \equiv \sum_{t=1}^{J_{i,T}} \Delta|mfe^h_{i,t}|,$$

where $J_{i,T}$ is the number of monetary policy announcements in country i in year T.

We estimate the following specification for Norway and Sweden separately, comparing them to New Zealand and Canada in separate regressions:

$$\Delta|MFE^h_{i,T}| = \psi + \gamma_1 I_i + \gamma_2 I_T + \beta I_i I_T + \varepsilon_t. \tag{6.5}$$

where $I_i = 0$ if i is the comparison country (New Zealand or Canada), $I_i = 1$ if i is Norway or Sweden, and $I_T = 1$ after Norges Bank or Riksbank began to publish IRPs. Hence, in the regression comparing Norway to New Zealand, $\psi + \gamma_1$ captures the average change in forecast errors around policy announcements in the period before Norges Bank began publishing IRPs, while γ_2 captures any source of change in forecast error responsiveness that coincided with Norway's introduction of IRPs and was common across New Zealand and Norway. Our main parameter of interest is β, as it captures the change in responsiveness that occurred after IRPs were introduced and that was not shared with New Zealand.

Table 6.3 presents the results for each country differenced against New Zealand and Canada in separate regressions. Because we now have aggregated the data to a yearly frequency, there are fewer observations (number of years multiplied by two, the number of countries being compared) and lower t-values. Still, we see that the previously emphasized results regarding IRPs remain qualitatively unchanged. The estimates of β are close to zero and insignificant in Norway, while they are negative and significant at the shorter horizons in Sweden. Hence, our previously found effects of publishing IRPs were not driven by omitted time-varying factors that Norway or Sweden shared with New Zealand or Canada.

[Insert Table 6.3 about here]

Finally, one might be concerned that spreads in the object being forecast in an FRA, i.e. premia in the interbank offered rates, have risen and become more volatile in the period after Norway and Sweden introduced IRPs, in particular after the widespread turbulence from Fall 2007. This pattern is documented across a variety of economies, see for instance Taylor and Williams (2009). The concern would be that interbank rates have become less predictable because their premia have become less predictable, and that this might weaken the negative response of MFEs to monetary

[15] In the appendix, we extend this analysis to a quarterly aggregation. As those results show, the quarterly aggregated data yields similar results as the yearly aggregation.

policy announcements in the later part of our sample. At this point, note first that the increase in premia is a wide international phenomenon, and therefore should have been picked up by our differencing against New Zealand and Canada above. In addition, when we look directly at estimated interbank rate premia after 2007, we find that to the extent they are correlated with our observed MFE changes, this comovement is *negative*. That is, if we let $prem_t$ denote the actual interbank premium at time t, the correlation between $\Delta|mfe_t^h|$ and $\Delta|prem_{t+h} - prem_t|$ is negative at all horizons h.[16] Hence, to the extent that premia affect our results, the effect is to *strengthen* the negative response of MFEs to monetary policy announcements after IRPs were introduced.

6.3.2 Target vs. Path Responses

Publication of IRPs is primarily considered a tool to communicate future policy intentions. However, our analysis above does not distinguish how markets react to communication of intentions from how markets react to monetary policy actions (the actual decision on the current short-term policy rate).

To distinguish actions from intentions, we rely on the method proposed by Gürkaynak et al. (2005). They use principal component analysis to decompose market interest rate reactions up to 4 quarters ahead into a "current federal funds rate target" factor and a "future path of policy" factor. These factors summarize uncorrelated sources of variation in the surprise movements in market rates. The former captures implemented policy actions, whereas the latter captures surprise changes in future short term rates. As the two are orthogonal by construction, the path factor represents reactions to communication about future policy that cannot be inferred from implemented decisions. Section 6.C in the appendix explains this method in more detail. Notably, the two factors together explain 98 percent of the total variation in interest rate reactions in Norway, and 96 percent in Sweden. Moreover, as documented in Appendix C, the path factor explains a substantial and increasing share of the interest rate reactions as the horizon increases. At the two-, three- and four-quarter horizons in Norway, the R-squared of the path factor is 0.36, 0.54 and 0.62, respectively. The corresponding numbers in Sweden are 0.34, 0.47, and 0.64.

Note that for the shortest horizon in this decomposition, we use the one-month-ahead interest rate implied by foreign exchange forward contracts.[18] Occasionally, the one-month rate matures after the next monetary policy meeting, and hence the change in this rate might in principle be contaminated by changes in expectations about future interest rate decisions. However, this occurred for only 9 out of 121 policy meetings in Sweden, and 11 out of 152 meetings in Norway. For 17 of these 20

[16] The correlations in Norway are -0.07, -0.02, -0.04, and -0.22, at the three, six, nine and twelve month horizons, respectively. In Sweden, these correlations are -0.53, -0.24, -0.30, and -0.35. The premia we use in these exercises are the spread between the interbank rates and the Overnight Indexed Swap (OIS). For Norway we use the Norges Bank estimated OIS due to the lack of a market based alternative, see Lund et al. (2016).

[18] This rate is the interest rate differential between USD and NOK in the FX swap market. In both Norway and Sweden, the FX swap market is one of the most liquid segments of the fixed-income market. We convert the difference between the FX forward rate and the spot rate to basis points. Then we use the high-frequency change in the 1-month interest rate differential around the monetary policy announcement as a measure of the market's immediate response to new information.

episodes the overlap was less than three days. It therefore constitutes a negligible problem for our purposes. Note that we choose the one-month rate rather than a shorter one because the one-month rate is less likely to be influenced by other factors than the information from the central bank within the window, especially banks' short term liquidity management.[19]

Figure 6.6 displays the target and path factors computed in 30-minute windows around policy announcements in Norway and Sweden. As before, red circles refer to policy announcements accompanied by an interest rate projection. We see that while both factors typically deviate from zero after policy announcements, the market reactions captured by the target factor are often negligible. This reflects that in several of the announcements, the policy action was to keep the short-term rate unchanged and in accordance with market expectations. Similar to what Gürkaynak et al. (2005) found for the US, Figure 6.6 also shows that the path factor tends to deviate substantially from zero around policy announcements in both Sweden and Norway.

[Insert Figure 6.6 about here]

To disentangle how the two types of market reactions contribute to forecast errors, we estimate the following specification for each horizon and country separately:

$$\Delta|mfe_t^h| = \psi + \gamma_1 Z_t^{tar} + \gamma_2 Z_t^{path} + \beta I_t + \alpha_1 I_t Z_t^{tar} + \alpha_2 I_t Z_t^{path} + \varepsilon_t, \tag{6.6}$$

where Z_t^{tar} and Z_t^{path} are the absolute values of the 30-minute target and path factors displayed in Figure 6.6. Table 6.4 provides the results from this regression.

[Insert Table 6.4 about here]

Focusing first on the estimated γ_1 and γ_2 in rows two and three of Table 6.4, we see that for Norway it was the target factor response that contributed to reduce forecast errors before IRPs were introduced. This holds at all horizons. For Sweden, our previously presented evidence showed that forecast errors were not systematically reduced by monetary policy announcements in the period before IRPs were introduced. Table 6.4 shows that this pattern applies in both the target and path dimensions, although the latter seem to have reduced forecast errors somewhat at longer horizons.

The bottom two rows of Table 6.4 provide estimates of how the target and path contributions to $\Delta|mfe_t^h|$ changed after IRPs were introduced (α_1 and α_2). In Norway, none of these estimates are significant, again suggesting that the introduction of IRPs did not improve market participants' forecasts of monetary policy. In Sweden, our estimates imply that the improvement of MFE-reactions

[19] Ideally, we would use standard proxies for short-term expectations like one-week Overnight Indexed Swap (OIS) rates, but these do not exist over our full sample period. However, in Sweden there are OIS rates available from 2007. This market is illiquid, but should still proxy for the expected policy rate over the next week. For the period where OIS rates have existed in Sweden (after 2007), one-week OIS rates and the one-month rate we utilize in our main analysis have a correlation of 0.7. In contrast, the correlation between one-week OIS rates and the short-term rate that is available over our full sample, one-week foreign exchange contracts, is only 0.5.

after IRPs were introduced predominantly came from the target factor, not from the path factor. The estimates of α_1 are negative at all horizons, though insignificantly so at the longest horizon. The estimates of α_2 indicate a slight negative contribution only at the shortest horizon, and at this horizon the estimate is not statistically significant.[20]

Together with the MFE movements revealed previously, Table 6.4 leaves us with a notable pattern. Publication of IRPs is generally considered as a means to more effectively communicate future policy intentions. The path factor by construction captures exactly this dimension of how markets interpret policy announcements. Yet, the introductions of IRPs have not increased the extent to which path factor reactions reduce forecast errors. Even in Sweden, where we have seen that MFEs began to fall upon policy announcements after IRPs were introduced, it is primarily the policy action, as captured by the target factor, that has guided markets on future monetary policy.

One might well question why the target factor reduces MFEs, and why this has only happened in Sweden. Here we can only speculate. One interpretation is that central banks may help market participants to better understand the rationale behind current policy *actions*. Thereby, markets might better infer what these actions imply for future policy. Moreover, it is plausible that there are diminishing returns here: If market participants initially struggle to interpret what current actions imply for future policy, better explanations by the central bank may have a sizeable effect. If market participants initially have a fairly clear understanding of what current actions imply for future policy decisions, there is less scope for improvement.[22] We find this interpretation plausible, since the improved reactions through the target factor occurred only in Sweden, where the target factor initially was not contributing to reduced forecast errors, whereas in Norway the target factor contributed to reduced forecast errors before IRPs were utilized and this did not improve further after IRPs were introduced.

6.4 Movements in Market Forecast Errors around Macroeconomic Data Releases

If IRPs serve to illuminate how the central bank systematically responds to changes in the economic environment, its "reaction function", then their presence should improve how market forecasts react to new macroeconomic information in general. We therefore extend our analysis to explore how MFEs have responded to the macroeconomic releases described in Section 6.2.2.

As an illustration, Figure 6.7 plots MFE-movements in 30-minute windows around the consumer price index (CPI) and industrial production releases. We see that market reactions are moderate for most of the releases, but there are several episodes of substantial responses. In Table 6.5 we

[20] None of these results change when we isolate the crisis period from 2007 to 2009. Details available upon request.

[22] At the extreme, the returns to communication must have decreasing returns: if markets already understand policy actions perfectly, then any increased effort to communicate will necessarily have zero effect on markets' mapping from actions to future policy.

examine a set of the arguably most important macro releases systematically. The first row in Table 6.5 shows that on average the MFE-movements have been negative, as one would expect. However, these average responses are small, reflecting the many releases with little new information in Figure 6.7.

[Insert Figure 6.7 about here]

For each country, the second and third lines of Table 6.5 show estimates from the specification in equation (6.2), where the units of observation are the MFE-changes around macro releases. The estimate of ψ reflects the average response of MFEs before IRPs were introduced, while β captures the change after IRPs were introduced. The β-estimates are small, non-negative, and insignificantly different from zero. There is nothing that indicates improved MFE-responses in the post-IRP period.

[Insert Table 6.5 about here]

Next, we zoom in on the monthly releases of the consumer price index (CPI), as this arguably will be the most important release for interest rates under inflation targeting. The results are displayed in Table 6.6. These give the same overall pattern as we saw in Table 6.5. In short, it does not seem that IRPs have guided markets to better interpret what macroeconomic news implies for future monetary policy.[23]

[Insert Table 6.6 about here]

6.5 Conclusion

To a considerable extent, the ultimate benefits from explicit monetary policy communication depend on how strongly it guides markets to better interpret what available information implies for future interest rate setting. We provide novel evidence on this exact issue. Consistent with the rich existing evidence from a variety of countries and periods, we do find that interest rates in forward contracts respond a great deal to central bank communication. However, the introduction of central bank interest rate projections (IRPs) has done little to improve these responses in the sense of bringing them closer to realized interest rates. Overall, central bank communication about future policy through IRPs has played only a limited role in guiding markets, at most.

We base our conclusion on two main findings. First, upon monetary policy announcements, the path factor of market reactions, which is to be interpreted as markets' response to central bank communication about the future, does not systematically move market forecasts closer to realized outcomes when central bank projections are present. It does seem that market reactions

[23]Isolating the crisis periods of 2007-2009 or 2008-2012 does not change these results in any substantial manner. In an earlier version of this paper we used data on market expectations to scale each release by the extent to which it surprised market participants. The results were essentially the same as in Table 6.5 here as well. Details available on request

to announced policy decisions were generally improved in Sweden after the Riksbank introduced its own IRPs, but these improvements arose only for the target factor, which captures the monetary policy action rather than communication of future policy intentions. In both countries, the path factor reactions are sizeable, but unlike target reactions they do not systematically bring market expectations closer to ex-post realizations.

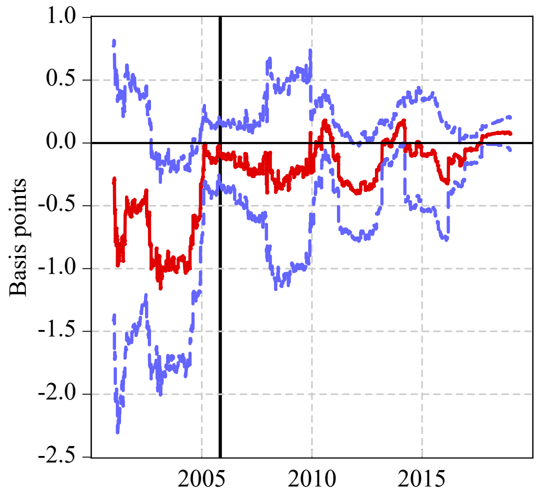
Second, upon macroeconomic releases, there is no sign that the presence of IRPs makes market rates respond more in the direction of ex-post realized interest rates. Hence, it does not seem that IRPs have guided markets toward a better understanding of what macroeconomic information implies for future monetary policy.

As discussed toward the end of Section 6.2.2, by interpreting our results in terms of market forecast errors, we are implicitly assuming that premia in FRAs are constant within the 30-minute windows we consider. While this assumption is widely imposed in the literature on central bank communication, it is worthwhile to reflect upon how our results might be reinterpreted if the assumption is violated. It could be that our observed movements in target factors reflect changes in market forecasts, whereas the path factor movements primarily reflect responses of forward premia to monetary policy announcements. This would explain the apparent paradox that after monetary policy announcements, path factor responses typically are large, but fail to reduce forecast errors systematically. Importantly though, even under this alternative interpretation of our results, the main insight from our analysis withstands: It does not seem that the practice of publishing interest rate projections has guided markets to better understand how the central banks will set interest rates in the future.

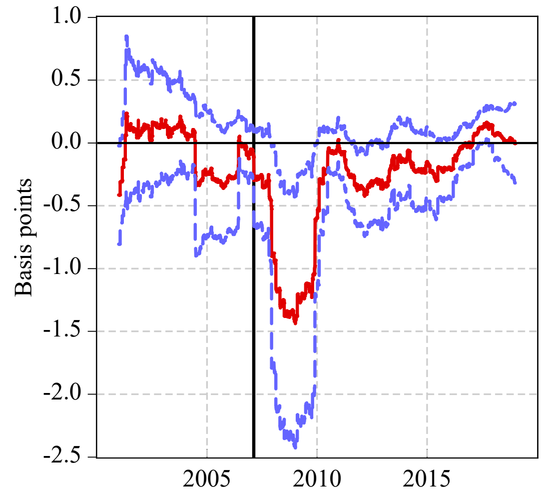
The practice of having central banks publish their own interest rate projections may be advocated on various grounds, and improving markets' understanding of future interest rates and central banks' reaction pattern are only two of them. Hence, we do not claim that publishing IRPs is without merit. However, we do believe our findings contrast with part of the motivation for publishing IRPs, as expressed by both policymakers and the academic literature. Moreover, our results motivate caution in interpreting the widespread evidence that markets respond to central bank communication. That pattern does not necessarily imply that the practice of publishing IRPs provides guidance on future policy.

Figures and Tables

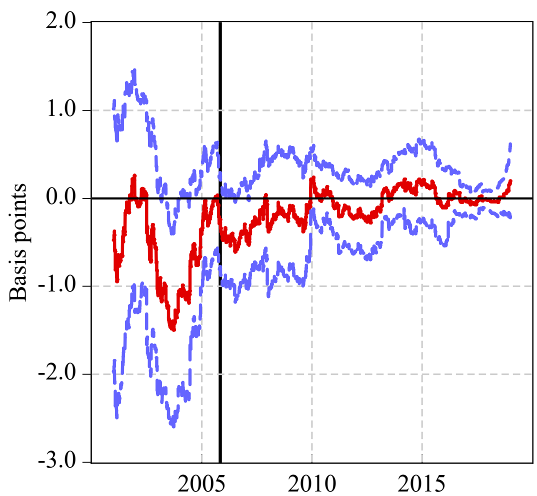
Figure 6.1
Time varying response of Market Forecast Errors (MFEs) to macro releases and monetary policy announcements



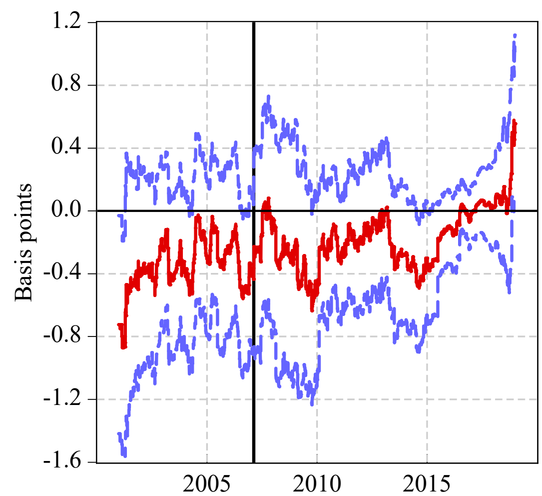
(a) Norway: Horizon 1



(b) Sweden: Horizon 1



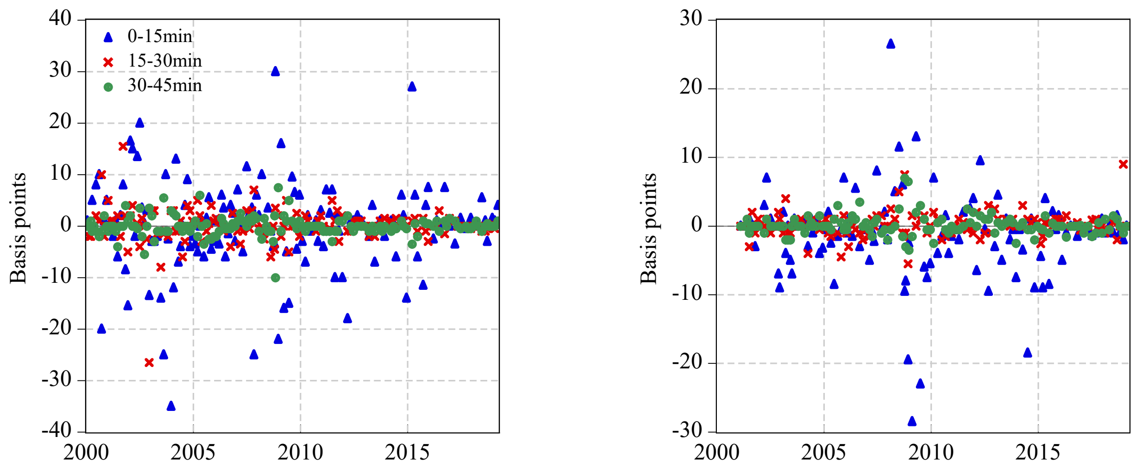
(c) Norway: Horizon 4



(d) Sweden: Horizon 4

Notes: Daily centered two-year rolling-window estimates of how market forecast errors (MFEs) respond to released macroeconomic data and monetary policy announcements, pooled. MFEs computed as the gap between ex post realized interest rates and corresponding 1- and 4-quarter forward rate agreements (FRAs) traded previously. Changes in MFEs are computed as the difference between MFEs immediately before a release and 30 minutes after. Negative numbers indicate reduced forecast errors. Estimation based on the method proposed by Swanson and Williams (2014). The bands cover two standard errors around each point estimate. Sample: January 2000 - March 2019.

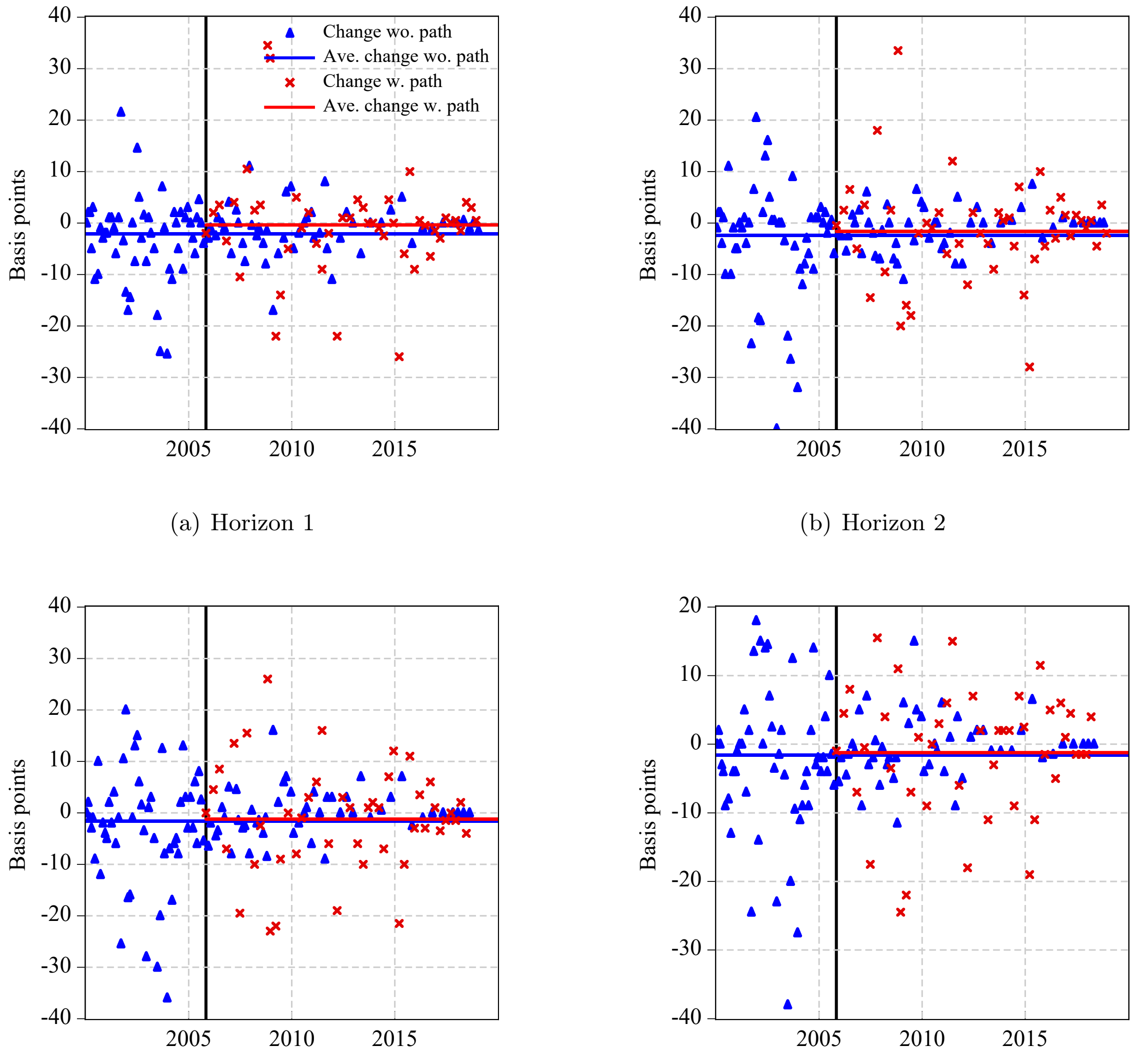
Figure 6.2
Alternative window-lengths for measuring market reactions after monetary policy releases



(a) Norway (b) Sweden

Notes: Movements of 1-year forward rate agreements (FRAs) after monetary policy announcements in Norway and Sweden. The responses are computed from immediately before to 15 minutes after, from 15 to 30 minutes after, and from 30 to 45 minutes after each monetary policy announcement. Sample: January 2000 - March 2019.

Figure 6.3
Market Forecast Error (MFE) response to monetary policy announcements: Norway



(a) Horizon 1

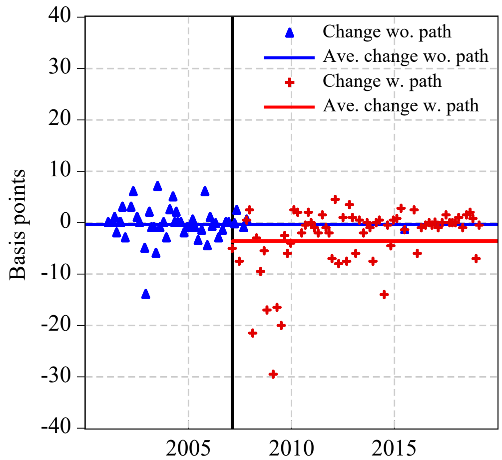
(b) Horizon 2

(c) Horizon 3

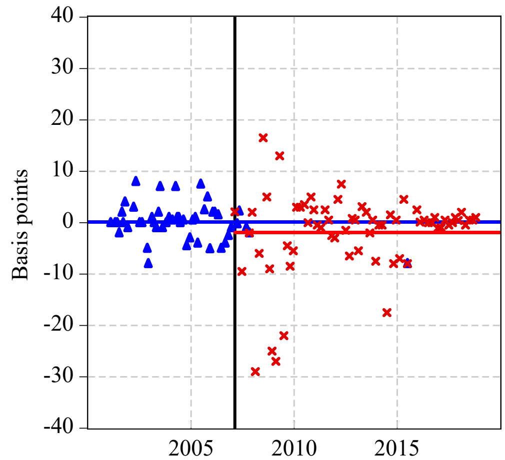
(d) Horizon 4

Notes: Change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after monetary policy announcements. Blue dots refer to policy meetings where no interest rate projection (IRP) was published together with the current interest rate decision, and the blue line is the average MFE change across these meetings. Red dots refer to meetings where an interest rate projection was published together with the current interest rate decision, and the red line is the average MFE change across these meetings. Sample: January 2000 - March 2019.

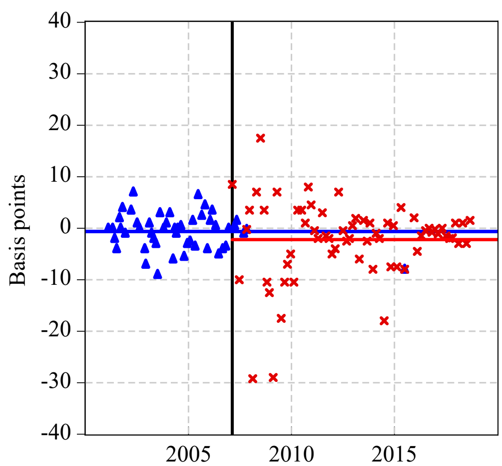
Figure 6.4
Market Forecast Error (MFE) response to monetary policy announcements: Sweden



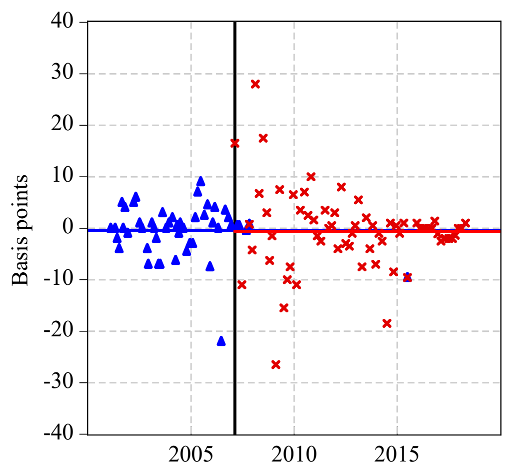
(a) Horizon 1



(b) Horizon 2



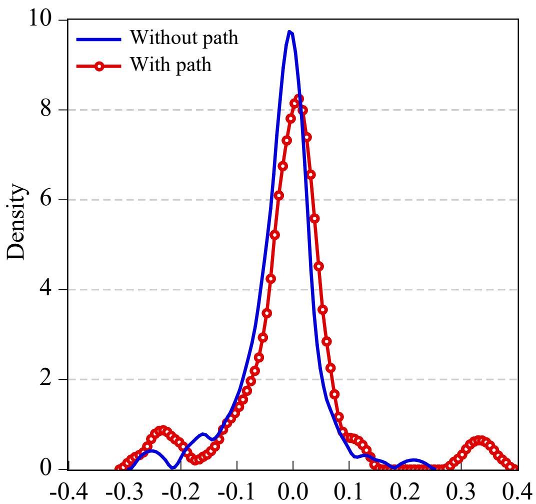
(c) Horizon 3



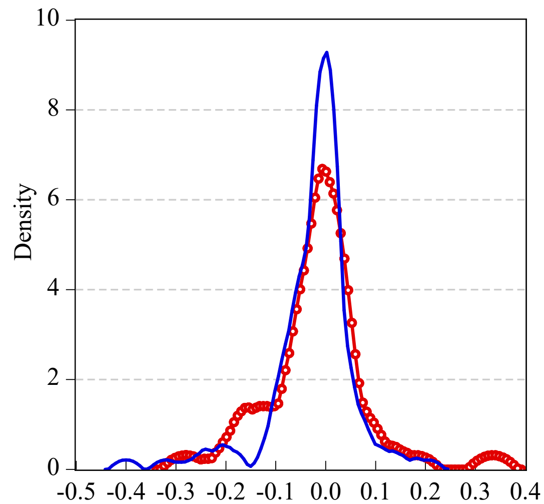
(d) Horizon 4

Notes: Change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after monetary policy announcements. Blue dots refer to policy meetings where no interest rate projection (IRP) was published together with the current interest rate decision, and the blue line is the average MFE change across these meetings. Red dots refer to meetings where an interest rate projection was published together with the current interest rate decision, and the red line is the average MFE change across these meetings. Sample: January 2000 - March 2019.

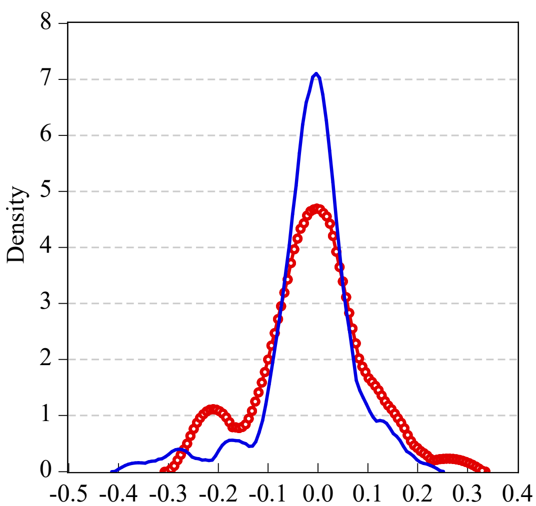
Figure 6.5
Distribution of Market Forecast Errors (MFE) movements around monetary policy announcements: Norway



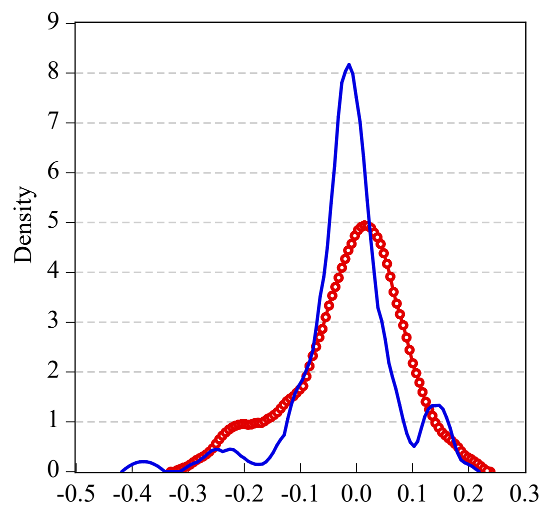
(a) Horizon 1



(b) Horizon 2



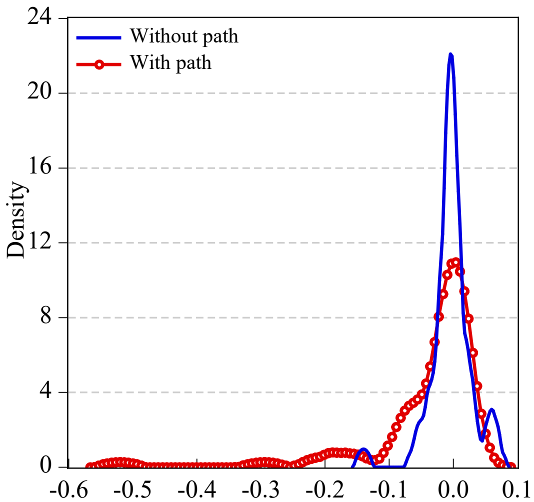
(c) Horizon 3



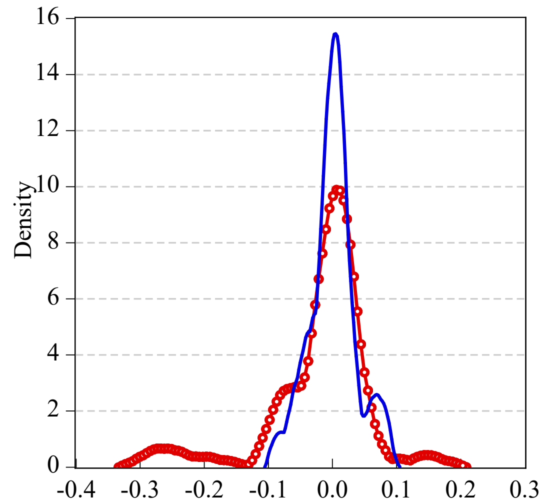
(d) Horizon 4

Notes: Estimated kernels for the distributions of change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after monetary policy announcements. The kernel distribution indicated by the blue line is for changes in MFEs when there is not interest rate projection (IRP), while red line are for distributions with IRP. Sample: January 2000 - March 2019.

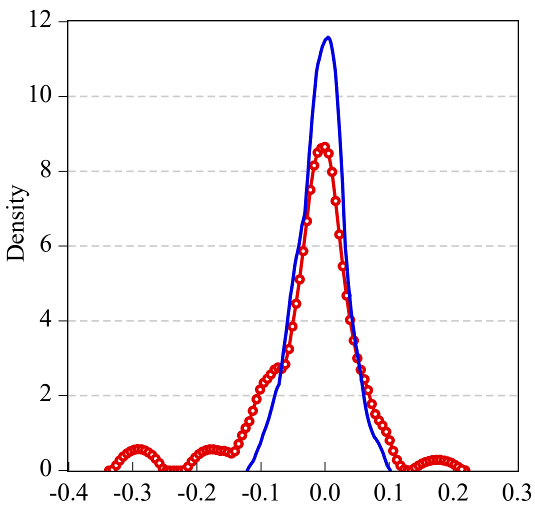
Figure 6.5
(Continued) Distribution of Market Forecast Errors (MFE) movements around monetary policy announcements: Sweden



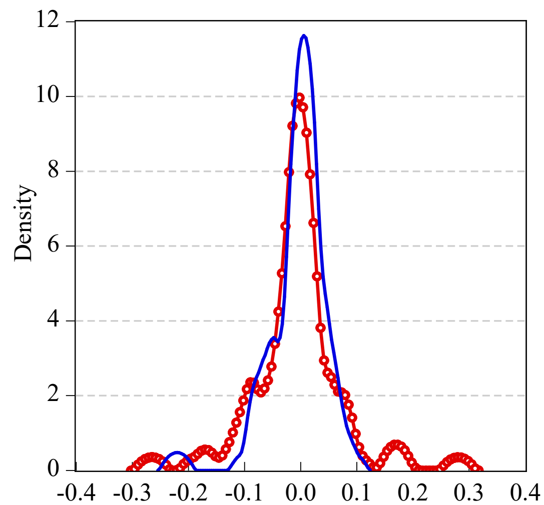
(a) Horizon 1



(b) Horizon 2



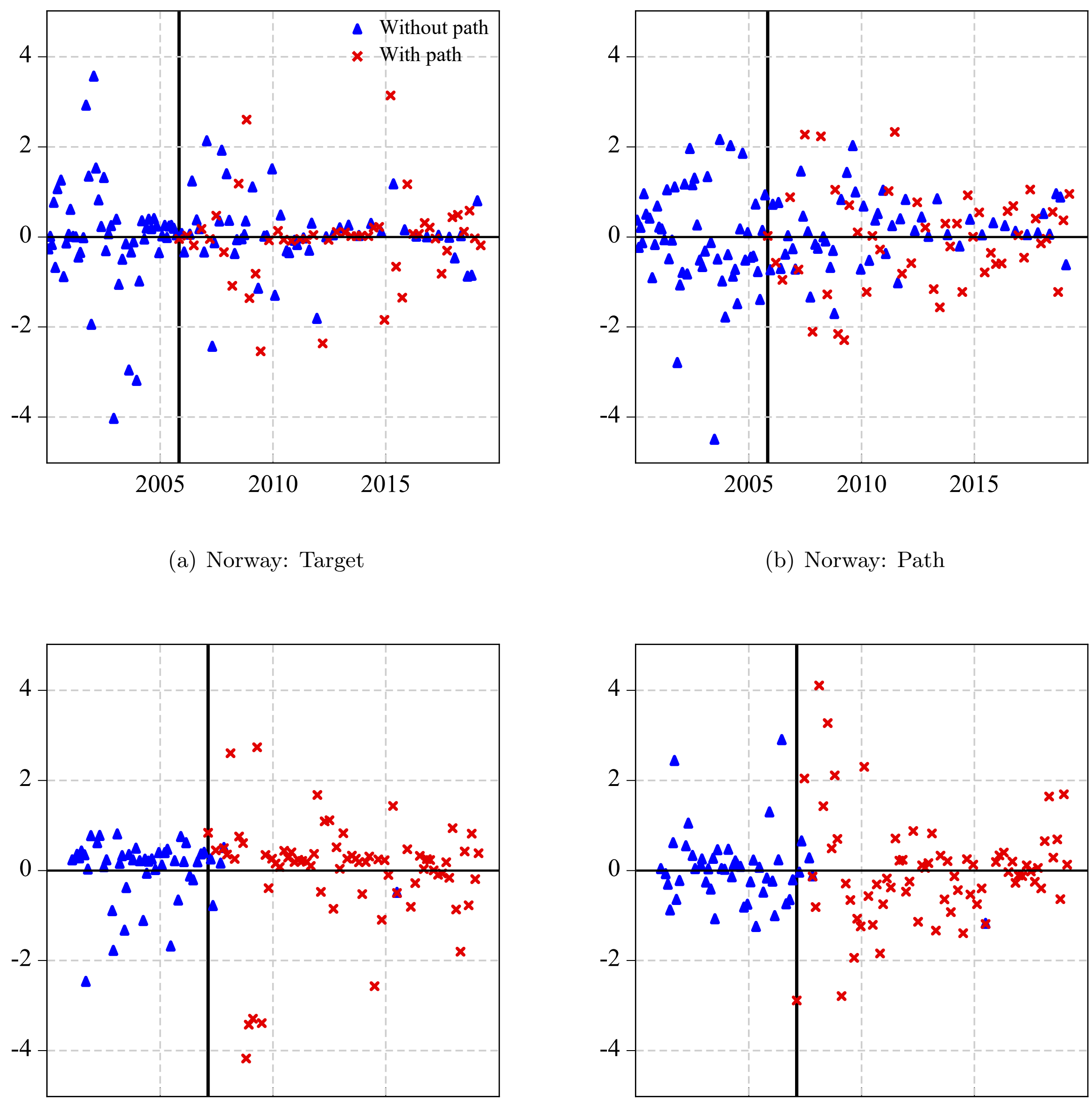
(c) Horizon 3



(d) Horizon 4

Notes: Estimated kernels for the distributions of change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after monetary policy announcements. The kernel distribution indicated by the blue line is for changes in MFEs when there is not interest rate projection (IRP), while red line are for distributions with IRP. Sample: January 2000 - March 2019.

Figure 6.6
Target and path responses to monetary policy announcements



(a) Norway: Target

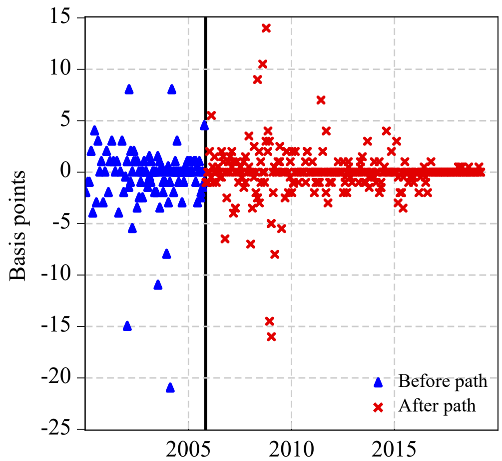
(b) Norway: Path

(c) Sweden: Target

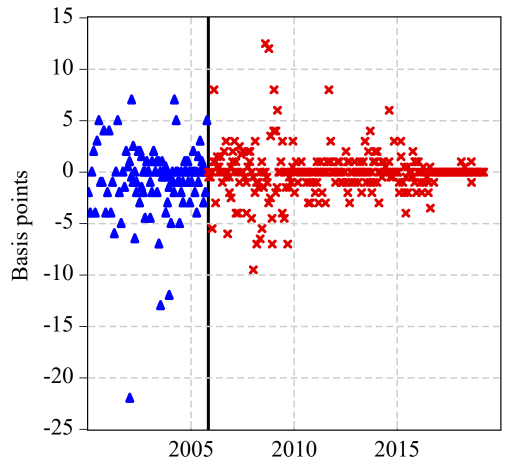
(d) Sweden: Path

Notes: Movements in the path and target factors of forward rate agreements (FRAs) from immediately before to 30 minutes after monetary policy announcements. Sample: January 2000 - March 2019.

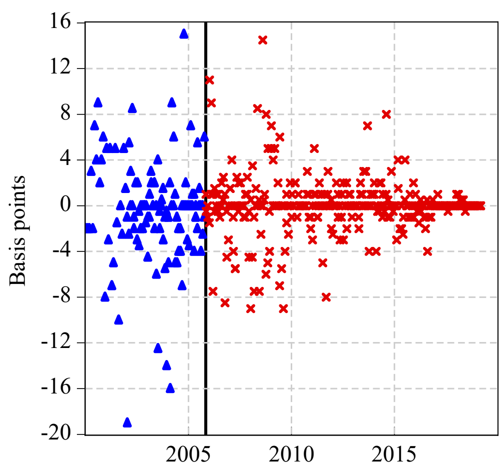
Figure 6.7
Market Forecast Error (MFE) responses to macro releases: Norway



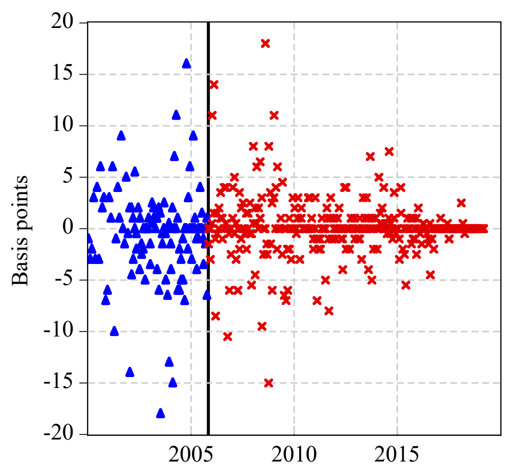
(a) Horizon 1



(b) Horizon 2



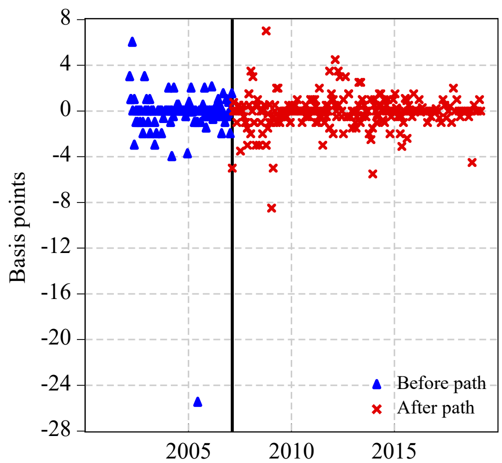
(c) Horizon 3



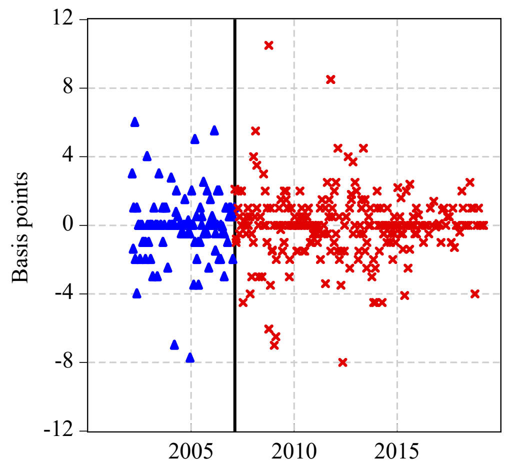
(d) Horizon 4

Notes: Change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after the monthly release of the consumer price index (CPI) and industrial production (IP) in Norway and Sweden. Sample: January 2000 - March 2019.

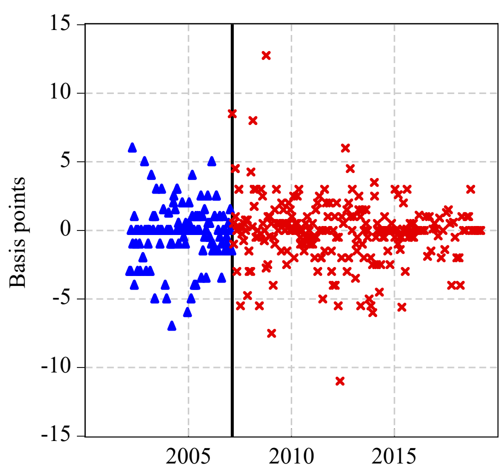
Figure 6.7
(Continued) Market Forecast Error (MFE) responses to macro releases: Sweden



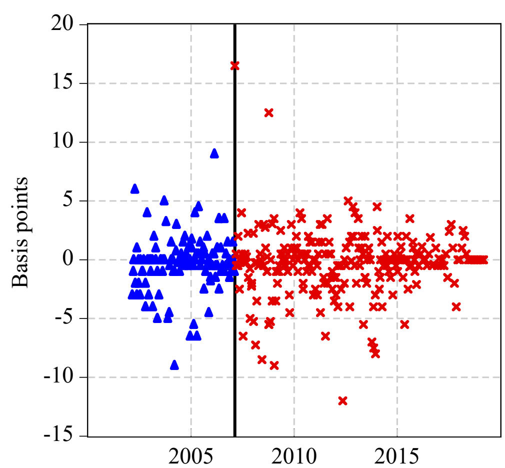
(a) Horizon 1



(b) Horizon 2



(c) Horizon 3



(d) Horizon 4

Notes: Change in Market Forecast Errors (MFEs) from immediately before to 30 minutes after the monthly release of the consumer price index (CPI) and industrial production (IP) in Norway and Sweden. Sample: January 2000 - March 2019.

Table 6.1
Market forecast error responses to monetary policy announcements. Norway

	A: Horizon 1				**B:** Horizon 2			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Before IRP (ψ)	-0.030	-0.030	-0.030	-0.030	-0.036	-0.036	-0.036	-0.036
	(-2.66)	(-2.65)	(-2.63)	(-2.63)	(-2.35)	(-2.34)	(-2.32)	(-2.32)
Change after IRP (β)	0.022				0.022			
	(1.59)				(1.29)			
Change after IRP,		0.026				0.020		
with IRP (β_1)		(1.38)				(0.94)		
Change after IRP,		0.018				0.024		
no IRP (β_2)		(1.41)				(1.48)		
Change after IRP,			0.017	0.023			0.024	0.024
with IRP, no crisis (β_1^{nc})			(1.10)	(1.40)			(1.23)	(1.12)
Change after IRP,			0.023	0.026			0.026	0.029
no IRP, no crisis (β_2^{nc})			(1.74)	(1.91)			(1.59)	(1.70)
Change after IRP,			0.075	0.032			-0.006	0.012
with IRP, crisis (β_1^{c})			(0.97)	(0.80)			(-0.09)	(0.34)
Change after IRP,			0.002	0.010			0.017	0.019
no IRP, crisis (β_2^{c})			(0.11)	(0.63)			(0.76)	(1.07)
Adjusted R^2	0.01	0.01	0.02	0.00	0.01	0.00	-0.01	-0.01
Observations	151	151	151	151	150	150	150	150
Average FE	0.168				0.339			

Notes: Regression results based on equations (2) to (4), with coefficient in question in parenthesis on each row. 'Before IRP' means the period before interest rate projections were introduced. 'Change after IRP' is the change in coefficient estimate after interest rate projections were introduced. In column marked (2) the post-IRP period is divided into monetary policy announcements that were accompanied by an IRP or not. The two columns marked (3) and (4) separates crisis from non-crisis periods, using two alternative crisis definitions. In column (3), a crisis dummy equals 1 only in the global financial crisis from 2008 to 2009, while column (4) extends the crisis dummy to the European sovereign debt crisis as well (2008-2012). Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Average FE means the average forecast error over the sample period, January 2000-March 2019. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.1
(Continued) Market forecast error responses to monetary policy announcements. Norway

	C: Horizon 3				**D:** Horizon 4			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Before IRP (ψ)	-0.030	-0.030	-0.030	-0.030	-0.027	-0.027	-0.027	-0.027
	(-1.93)	(-1.93)	(-1.91)	(-1.91)	(-1.80)	(-1.79)	(-1.78)	(-1.78)
Change after IRP (β)	0.024				0.019			
	(1.36)				(1.13)			
Change after IRP,		0.018				0.015		
with IRP (β_1)		(0.83)				(0.71)		
Change after IRP,		0.029				0.023		
no IRP (β_2)		(1.72)				(1.39)		
Change after IRP,			0.027	0.027			0.023	0.022
with IRP, no crisis (β_1^{nc})			(1.25)	(1.21)			(1.14)	(1.03)
Change after IRP,			0.024	0.024			0.020	0.019
no IRP, no crisis (β_2^{nc})			(1.42)	(1.36)			(1.18)	(1.14)
Change after IRP,			-0.027	0.002			-0.031	0.002
with IRP, crisis (β_1^{c})			(-0.45)	(0.05)			(-0.63)	(0.06)
Change after IRP,			0.047	0.035			0.036	0.027
no IRP, crisis (β_2^{c})			(1.90)	(1.84)			(1.40)	(1.42)
Adjusted R^2	0.01	0.00	0.01	0.00	0.00	0.00	0.00	-0.01
Observations	147	147	147	147	145	145	145	145
Average FE	0.548				0.710			

Notes: Regression results based on equations (2) to (4), with coefficient in question in parenthesis on each row. 'Before IRP' means the period before interest rate projections were introduced. 'Change after IRP' is the change in coefficient estimate after interest rate projections were introduced. In column marked (2) the post-IRP period is divided into monetary policy announcements that were accompanied by an IRP or not. The two columns marked (3) and (4) separates crisis from non-crisis periods, using two alternative crisis definitions. In column (3), a crisis dummy equals 1 only in the global financial crisis from 2008 to 2009, while column (4) extends the crisis dummy to the European sovereign debt crisis as well (2008-2012). Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Average FE means the average forecast error over the sample period, January 2000-March 2019. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.2
Market forecast error responses to monetary policy announcements. Sweden

	A: Horizon 1				**B:** Horizon 2			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Before IRP (ψ)	-0.004	-0.004	-0.004	-0.004	0.003	0.003	0.003	0.003
	(-0.70)	(-0.70)	(-0.70)	(-0.70)	(0.57)	(0.56)	(0.56)	(0.56)
Change after IRP (β)	-0.030				-0.022			
	(-2.76)				(-2.15)			
Change after IRP,		-0.008	-0.009			-0.008	-0.015	
no crisis (β^{nc})		(-1.13)	(-1.28)			(-1.13)	(-1.78)	
Change after IRP,		-0.129	-0.058			-0.080	-0.031	
crisis (β^{c})		(-3.36)	(-2.75)			(-2.16)	(-1.62)	
Change after IRP,				-0.041				-0.03
no leaning (β^{nl})				(-2.65)				(-2.18)
Change after IRP,				-0.012				-0.008
leaning (β^{l})				(-1.34)				(-0.80)
Adjusted R^2	0.03	0.31	0.10	0.05	0.02	0.13	0.02	0.03
Observations	121	121	121	121	119	119	119	119
Average FE	0.218				0.277			

Notes: Regression results based on equations (2) and (4), with coefficient in question in parenthesis on each row (the D_t-dummy in eq. (4) not relevant for Sweden). 'Before IRP' means the period before interest rate projections were introduced. 'Change after IRP' is the change in coefficient estimate after interest rate projections were introduced. The two columns marked (2) and (3) separates crisis from non-crisis periods, using two alternative crisis definitions. In column (2), a crisis dummy equals 1 only in the global financial crisis from 2008 to 2009, while in column (3) the crisis dummy extends into the European sovereign debt crisis as well (2008-2012). Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Average FE means the average forecast error over the sample period, January 2000- March 2018. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.2
(Continued) Market forecast error responses to monetary policy announcements. Sweden

	C: Horizon 3				**D:** Horizon 4			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Before IRP (ψ)	-0.006	-0.006	-0.006	-0.006	-0.004	-0.004	-0.004	-0.004
	(-1.07)	(-1.06)	(-1.06)	(-1.06)	(-0.47)	(-0.47)	(-0.47)	(-0.47)
Change after IRP (β)	-0.015				-0.001			
	(-1.52)				(-0.06)			
Change after IRP, no crisis (β^{nc})		-0.006	-0.011			-0.003	-0.010	
		(-0.73)	(-1.22)			(-0.32)	(-0.87)	
Change after IRP, crisis (β^{c})		-0.056	-0.021			0.010	0.011	
		(-1.57)	(-1.16)			(0.28)	(0.58)	
Change after IRP, no leaning (β^{nl})				-0.021				0.002
				(-1.49)				(0.16)
Change after IRP, leaning (β^{l})				-0.007				-0.005
				(-0.67)				(-0.39)
Adjusted R^2	0.01	0.06	0.00	0.00	-0.01	-0.01	0.00	-0.02
Observations	118	118	118	118	116	116	116	116
Average FE	0.596				0.938			

Notes: Regression results based on equations (2) and (4), with coefficient in question in parenthesis on each row (the D_t-dummy in eq. (4) not relevant for Sweden). 'Before IRP' means the period before interest rate projections were introduced. 'Change after IRP' is the change in coefficient estimate after interest rate projections were introduced. The two columns marked (2) and (3) separates crisis from non-crisis periods, using two alternative crisis definitions. In column (2), a crisis dummy equals 1 only in the global financial crisis from 2008 to 2009, while in column (3) the crisis dummy extends into the European sovereign debt crisis as well (2008-2012). Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Average FE means the average forecast error over the sample period, January 2000 - March2018. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.3
Difference in differences - Norway and Sweden

	Horizon: 1	2	3	4	Horizon: 1	2	3	4
	I: RBNZ							
	Ia: Norges Bank vs RBNZ				**Ib:** Riksbank vs RBNZ			
Constant (ψ)	-0.047	-0.016	0.005	0.013	-0.042	-0.020	-0.005	0.002
	(-2.97)	(-0.77)	(0.52)	(0.90)	(-2.89)	(-1.06)	(-0.36)	(0.09)
Country (γ_1)	0.016	-0.020	-0.037	-0.042	0.038	0.023	0.000	-0.005
	(1.25)	(-1.21)	(-2.06)	(-1.61)	(2.43)	(1.14)	(-0.04)	(-0.25)
IRP-period (γ_2)	0.036	0.017	0.000	0.003	0.031	0.024	0.015	0.022
	(1.62)	(0.68)	(-0.01)	(0.15)	(1.39)	(1.04)	(0.76)	(1.05)
IRP-period×country	**-0.015**	**0.005**	**0.027**	**0.020**	**-0.056**	**-0.044**	**-0.031**	**-0.024**
(β)	**(-0.93)**	**(0.26)**	**(1.13)**	**(0.68)**	**(-1.97)**	**(-1.66)**	**(-1.38)**	**(-0.98)**
Adjusted R^2	0.03	0.03	0.03	0.11	0.00	-0.01	0.03	0.04
Observations (years×2)	40	38	38	38	39	37	37	37
	II: Bank of Canada							
	IIa: Norges Bank vs BoC				**IIb:** Riksbank vs BoC			
Constant (ψ)	-0.032	-0.031	-0.004	-0.014	-0.032	-0.030	-0.005	-0.009
	(-2.52)	(-1.96)	(-0.59)	(-1.56)	(-3.09)	(-2.21)	(-0.93)	(-0.96)
Country (γ_1)	0.000	-0.005	-0.028	-0.015	0.028	0.032	0.000	0.006
	(0.03)	(-0.21)	(-1.68)	(-0.72)	(2.51)	(2.42)	(-0.04)	(0.51)
IRP-period (γ_2)	0.016	0.024	-0.004	0.011	0.018	0.024	-0.002	0.003
	(1.17)	(1.43)	(-0.50)	(0.93)	(1.57)	(1.61)	(-0.32)	(0.29)
IRP-period×country	**0.005**	**-0.002**	**0.031**	**0.012**	**-0.043**	**-0.043**	**-0.013**	**-0.006**
(β)	**(0.28)**	**(-0.06)**	**(1.67)**	**(0.57)**	**(-2.56)**	**(-2.50)**	**(-1.15)**	**(-0.42)**
Adjusted R^2	0.03	0.12	0.11	0.04	0.03	0.06	0.02	-0.09
Observations (years×2)	39	37	37	37	38	36	36	36

Notes: Regression results from the difference in difference specification in equation (5), comparing Norway and Sweden to New Zealand and Canada. Coefficient-symbol in parenthesis on each row. IRP is short for interest rate projection. Market forecast errors (MFE) are aggregated to a yearly sum for each country. In panel Ia, the yearly sum of changes in forecast errors around monetary policy announcements in Norway are compared to those in New Zealand before and after Norges Bank introduced IRPs. Panel Ib reports results from the same exercise, but now for Sweden and New Zealand. In panels IIa and b, the control country is Canada instead of New Zealand. The difference-in-difference coefficient of interest is 'IRP-period×country'. Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Sample period: January 2000 - March 2019. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.4
Path vs. target factor

	Horizon: 1	2	3	4
	A: Norway			
Constant (ψ)	0.010	0.024	0.023	0.014
	(0.93)	(1.53)	(1.14)	(0.55)
Target Factor (γ_1)	-0.030	-0.067	-0.057	-0.043
	(-1.59)	(-4.01)	(-3.59)	(-2.73)
Path Factor (γ_2)	-0.021	-0.013	-0.014	-0.011
	(-1.58)	(-0.53)	(-0.43)	(-0.26)
Change after IRP (β)	-0.018	-0.019	-0.008	-0.004
	(-1.09)	(-1.05)	(-0.35)	(-0.14)
Target×IRP (α_1)	0.018	0.046	0.046	0.023
	(0.58)	(1.59)	(1.74)	(1.04)
Path×IRP (α_2)	0.030	0.002	-0.009	0.000
	(1.20)	(0.06)	(-0.22)	(0.01)
Adjusted R^2	0.06	0.21	0.14	0.09
Observations	151	150	147	145
	B: Sweden			
Constant (ψ)	0.006	0.006	0.001	0.012
	(0.96)	(1.39)	(0.11)	(1.28)
Target Factor (γ_1)	-0.024	0.009	0.002	0.006
	(-1.41)	(0.53)	(0.11)	(0.28)
Path Factor (γ_2)	0.005	-0.014	-0.014	-0.036
	(0.43)	(-1.63)	(-1.61)	(-1.39)
Change after IRP (β)	0.018	0.014	0.015	-0.018
	(2.07)	(1.33)	(1.26)	(-1.05)
Target×IRP (α_1)	-0.046	-0.052	-0.039	-0.029
	(-1.84)	(-2.27)	(-1.95)	(-1.09)
Path×IRP (α_2)	-0.014	0.005	0.001	0.060
	(-0.98)	(0.21)	(0.05)	(1.75)
Adjusted R^2	0.58	0.29	0.23	0.07
Observations	121	119	118	116

Notes: Regression results based on equation (6), where change in forecast error is regressed on the absolute value of target and path factors. Our computation of target and path factors is outlined in Appendix C and follows the procedure of Gürkaynak et al. (2005). 'IRP' is short for interest rate projection. Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Sample period: 01.01.2000-03.31.2019. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.5
Change in market forecast errors around macro releases

	Horizon: 1		2		3		4	
				A: Norway				
Average	-0.001		-0.001		0.000		-0.001	
	(-1.49)		(-2.48)		(-0.46)		(-1.04)	
Before IRP (ψ)		-0.002		-0.003		-0.001		-0.003
		(-1.39)		(-1.58)		(-0.37)		(-1.45)
Change after IRP (β)		0.002		0.002		0.001		0.003
		(1.01)		(0.89)		(0.28)		(1.35)
Adjusted R^2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Observations	1255	1255	1227	1227	1267	1267	1188	1188
				B: Sweden				
Average	-0.001		0.000		-0.001		-0.002	
	(-1.76)		(-0.02)		(-1.78)		(-2.97)	
Before IRP (ψ)		-0.001		0.000		-0.003		-0.003
		(-0.88)		(-0.19)		(-2.42)		(-2.73)
Change after IRP (β)		0.000		0.000		0.002		0.002
		(0.32)		(0.21)		(1.75)		(1.35)
Adjusted R^2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Observations	1008	1008	987	987	1015	1015	959	959

Notes: The change in market forecast errors around releases of macro economic data in Norway and Sweden, at 4 different horizons. Coefficients from the specification in equation (7) in parenthesis on each row. The releases are: domestic consumer price index (CPI), domestic industrial production, trade balance, purchasing managers sentiment index (PMI), unemployment rate, gross domestic product (GDP), retail sales, economic tendency indicator (Sweden only), oil investments (Norway only), aggregate credit (K2, Norway only). 'IRP' is short for interest rate projection. Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Sample period: 01.01.2000-03.31.2019. t-values in parenthesis (Newey-West corrected standard errors).

Table 6.6
Change in market forecast errors around CPI releases

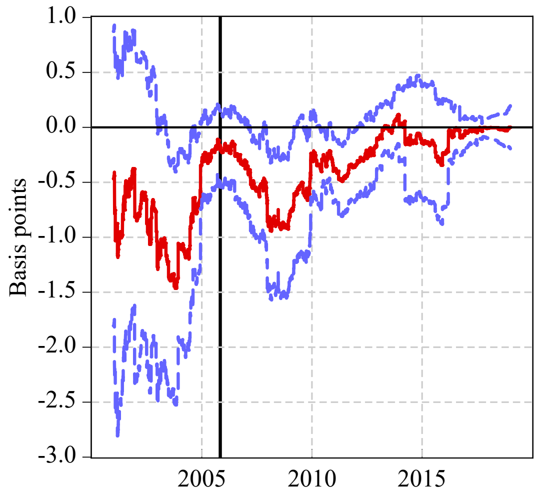
	Horizon: 1	2	3	4
	A: Norway			
Before IRP (ψ)	-0.008	-0.012	-0.007	-0.010
	(-1.68)	(-2.15)	(-0.92)	(-1.47)
Change after IRP (β)	0.007	0.011	0.007	0.013
	(1.30)	(1.80)	(0.96)	(1.64)
Adjusted R^2	0.01	0.01	0.00	0.01
Observations	231	228	225	222
	B: Sweden			
Before IRP (ψ)	-0.006	-0.001	-0.005	-0.004
	(-1.31)	(-0.41)	(-1.33)	(-0.86)
Change after IRP (β)	0.005	0.002	0.005	0.000
	(0.99)	(0.43)	(1.07)	(0.07)
Adjusted R^2	0.00	0.00	0.00	-0.01
Observations	206	203	200	197

Notes: The change in market forecast errors around releases of the consumer price index in Norway and Sweden, at 4 different horizons. Coefficients from specification in equation (7) in parenthesis on each row 'IRP' is short for interest rate projection. Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Sample period: 01.01.2000-03.31.2019. t-values in parenthesis (Newey-West corrected standard errors).

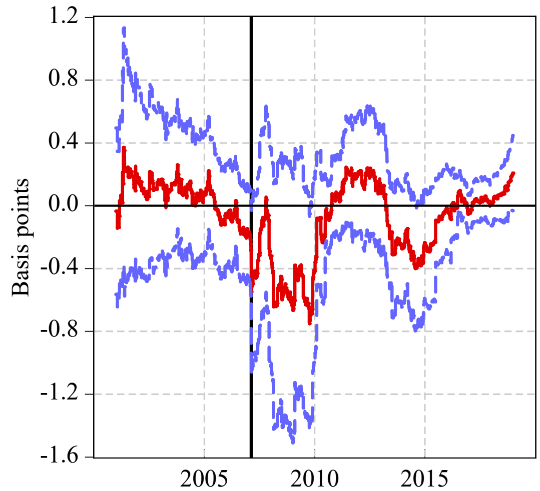
Appendix

6.A Additional Figures and Tables

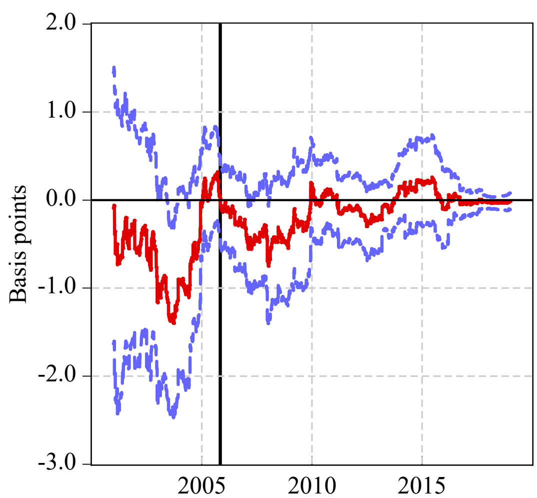
Figure 6.A.1
Time varying MFE responses to macro releases and monetary policy announcements



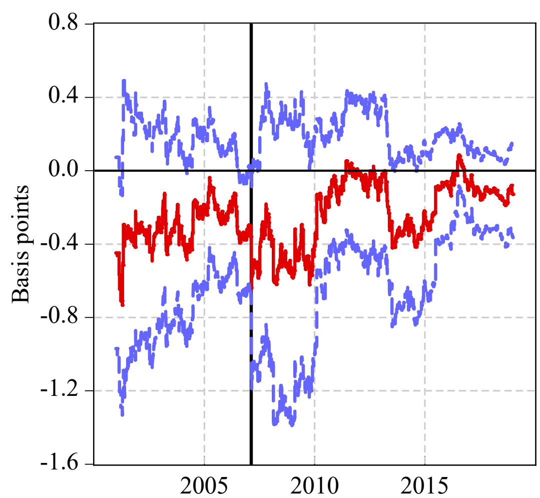
(a) Norway: Horizon 2



(b) Sweden: Horizon 2



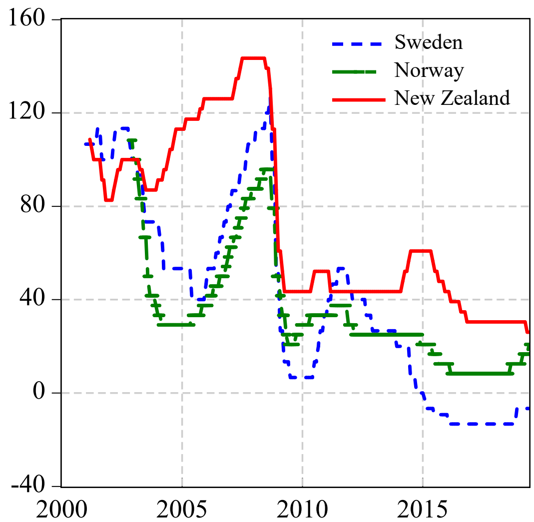
(c) Norway: Horizon 3



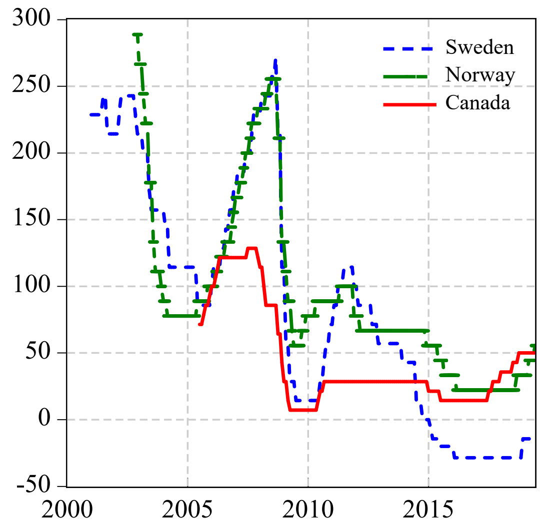
(d) Sweden: Horizon 3

Notes: Daily centered two-year rolling-window estimates of how market forecast errors (MFEs) respond to released macroeconomic data and monetary policy announcements, pooled. MFEs computed as the gap between ex post realized interest rates and corresponding 2- and 3-quarter forward interest rate agreements traded previously. Changes in MFEs are computed as the difference between MFEs immediately before a release and 30 minutes after. Negative numbers indicate reduced forecast errors. Estimation based on the method proposed by Swanson and Williams (2014). The bands cover two standard errors around each point estimate.

Figure 6.A.2
Comparing key policy rates in Sweden and Norway with New Zealand and Canada



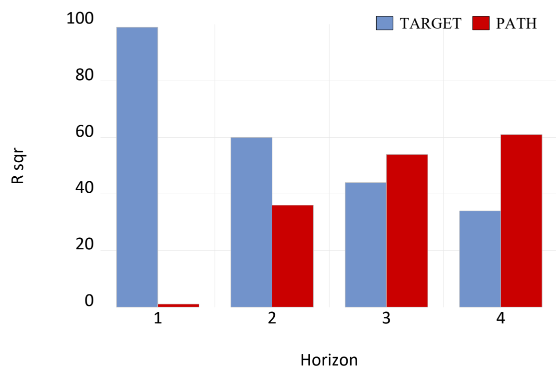
(a) New Zealand



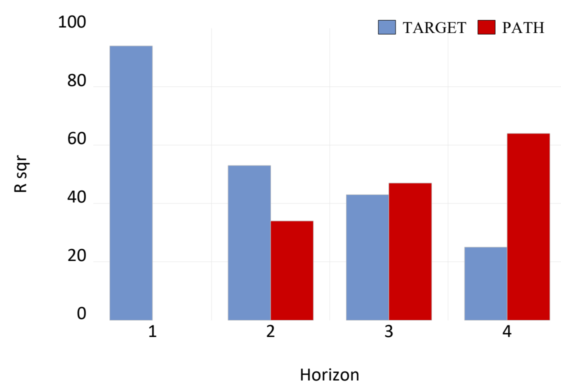
(b) Canada

Notes: Figure compares the Swedish and Norwegian key policy rates to those of New Zealand (panel a) and Canada (panel b). All rates indexed to 100 in January 2003 in panel a, and to 100 in January 2006 in panel b.

Figure 6.A.3
Explanatory Power of Path and Target Factors for Interest Rates



(a) Norway



(b) Sweden

Notes: The individual contributions of the two orthogonal factors "target" and "path" in explaining the responses of the 1-month rate, the second, third and fourth IMM FRA (respectively horizon 1 to 4) in 30-minute windows around monetary policy announcements. Each factor's individual contribution is measured by the R-squared from standard univariate OLS regressions with the respective interest-rate change as dependent variable and the respective factor as explanatory variable.

Table 6.A.1
Difference in differences - Norway and Sweden (Quarterly data)

	Horizon: 1	2	3	4	Horizon: 1	2	3	4
	I: RBNZ							
	Ia: Norges Bank vs RBNZ				**Ib:** Riksbank vs RBNZ			
Constant (ψ)	-0.055	-0.022	0.003	0.021	-0.047	-0.024	-0.008	0.002
	(-4.04)	(-1.28)	(0.24)	(1.40)	(-4.08)	(-1.76)	(-0.68)	(0.11)
Country (γ_1)	0.021	-0.019	-0.039	-0.054	0.045	0.028	0.006	-0.001
	(1.34)	(-0.81)	(-1.50)	(-2.03)	(3.82)	(1.93)	(0.52)	(-0.04)
IRP-period (γ_2)	0.043	0.022	0.003	-0.008	0.036	0.029	0.019	0.021
	(2.18)	(1.13)	(0.16)	(-0.42)	(1.84)	(1.62)	(1.10)	(1.06)
IRP-period×country	-0.022	0.004	0.026	0.034	-0.065	-0.048	-0.040	-0.025
(β)	(-1.14)	(0.14)	(0.89)	(1.12)	(-3.05)	(-2.33)	(-1.81)	(-1.09)
Adjusted R^2	0.01	0.02	0.02	0.04	0.02	0.01	0.01	0.00
Obs. (quarters×2)	151	149	147	145	147	145	143	141
	II: Bank of Canada							
	IIa: Norges Bank vs BoC				**IIb:** Riksbank vs BoC			
Constant (ψ)	-0.028	-0.028	-0.005	-0.013	-0.029	-0.024	-0.004	-0.005
	(-2.62)	(-1.86)	(-0.39)	(-1.00)	(-3.15)	(-1.87)	(-0.39)	(-0.49)
Country (γ_1)	-0.005	-0.013	-0.031	-0.020	0.027	0.028	0.002	0.006
	(-0.40)	(-0.49)	(-1.49)	(-1.00)	(2.50)	(2.08)	(0.24)	(0.54)
IRP-period (γ_2)	0.012	0.021	-0.002	0.009	0.014	0.018	-0.003	-0.001
	(1.05)	(1.36)	(-0.14)	(0.62)	(1.41)	(1.31)	(-0.25)	(-0.11)
IRP-period×country	0.008	0.004	0.031	0.017	-0.043	-0.038	-0.018	-0.003
(β)	(0.52)	(0.16)	(1.38)	(0.78)	(-2.95)	(-2.06)	(-1.13)	(-0.19)
Adjusted R^2	0.00	0.02	0.02	0.01	0.03	0.01	0.00	-0.02
Obs. (quarters×2)	148	146	144	142	144	142	140	138

Notes: Regression results from the difference in difference specification in equation (5), comparing Norway and Sweden to New Zealand and Canada. Coefficient-symbol in parenthesis on each row. IRP is short for interest rate projection. Market forecast errors (MFE) are aggregated to a yearly sum for each country. In panel Ia, the yearly sum of changes in forecast errors around monetary policy announcements in Norway are compared to those in New Zealand before and after Norges Bank introduced IRPs. Panel Ib reports results from the same exercise, but now for Sweden and New Zealand. In panels IIa and b, the control country is Canada instead of New Zealand. The difference-in-difference coefficient of interest is 'IRP-period×country'. Horizon 1 to 4 represent the next four IMM-maturity dates, approximately 3-month, 6-month, 9-month and 1-year ahead horizons respectively. Sample period: 01.01.2000-03.31.2019. t-values in parenthesis (Newey-West corrected standard errors).

6.B Rolling Window Regressions

We here summarize how we estimate the rolling-window regressions in Figure 6.1 and 6.A.1. Our approach to pooling different releases follows Swanson and Williams (2014), who study interest rate reactions to macroeconomic news.

For each horizon h, we first estimate the non-linear least specification

$$\Delta|mfe_t^h| = \delta^T \boldsymbol{\beta} \mathbf{I_t} + \varepsilon_t, \tag{6.B.1}$$

where $\mathbf{I_t}$ is a vector of dummies that each equals 1 whenever one specific macro release or a monetary policy announcement takes place. Next, $\boldsymbol{\beta}$ is a vector of coefficients on these dummies. In contrast, δ^T consists of a year-specific scalars that may take on different values in each calendar year T. Hence, the $\boldsymbol{\beta}$-vector scales how much each release typically affects market forecast errors, across all years in our sample. The coefficient δ^T captures how the influence of all releases combined varies over time.

Next, to move from calendar years to windows centered around each release, we estimate rolling regressions of

$$\Delta|mfe_t^h| = \delta^\tau \hat{\mathbf{I}}_\mathbf{t} + \varepsilon_t, \tag{6.B.2}$$

where $\hat{\mathbf{I}}_\mathbf{t} = \hat{\boldsymbol{\beta}} \mathbf{I_t}$ uses the estimated value of $\hat{\boldsymbol{\beta}}$ from (6.B.1). Our rolling estimation of (6.B.2) uses two years of data centered at each day of release, τ. Hence, the resultant estimates of δ^τ reflect how a "generic release" affects MFEs at time τ. To account for two-stage sampling uncertainty, the standard errors estimated in (6.B.2) are scaled up by a factor based on the standard errors estimated in (6.B.1) and interpolation between them.

6.C Target vs. Path Decomposition

We here summarize how we decompose market reactions into a target and a path factor, the method of Gürkaynak et al. (2005).

The starting point is the equation:

$$X = F\Lambda + \eta \tag{6.C.1}$$

where X is a matrix in which each row corresponds to a monetary policy announcements at specific point in time, and each column contains the 30-minute change of a specific asset price around each announcement. The prices we consider are the FRAs described in section 6.2.2. Importantly though, to obtain a shorter-horizon interest rate than the 3-month FRA, we use the one-month interest rate implied by foreign exchange forward contracts. F is a matrix of unobserved factors, Λ is a matrix of factor loadings and η is white noise.

The key finding of the now vast empirical literature following Gürkaynak et al. (2005), is that two factors (two appropriately composed columns of F) suffice to explain the data in X. The same has been found to apply to Norway, see for instance Brubakk et al. (2017). In total, the two first factors together explain 98 and 96 percent of our data's interest rate reactions in Norway and Sweden, respectively. Denote these two factors F_1 and F_2. To obtain a structural interpretation of them, they are rotated to yield two new orthogonal factors Z_1 and Z_2 which explain the data in X to exactly the same extent as F_1 and F_2 did, but with the additional restriction that Z_2 has no effect on one-month fx-forward implied interest rates (our measure of the instant effect of monetary policy action not connected to signals about future policy). The rotation is simply $Z = FU$, where $F = [F_1, F_2]$, $Z = [Z_1, Z_2]$, and U is a 2×2 matrix constructed such that Z_2 on average is associated with no change in the closest FRA. Hence, Z_1 is associated with variation in the current policy target rate, whereas Z_2 captures any other information than the current policy rate that affects the expected path of the monetary policy rate over the next year. The names follow: "target" and "path" factors.

Figure 6.A.3 shows how much each the target and path factor contribute to explaining interest rate reactions at different horizons in Norway and Sweden. The figure simply displays the R-squared from the regression

$$\Delta i_t^h = \gamma Z_t^j + \epsilon_t, \tag{6.C.2}$$

where Δi_t^h is the response of the h-horizon interest rate to a monetary policy announcement at time t and Z_t^j is factor j at time t, where j is either target or path. Recall that because the two factors are orthogonal by construction, the sum of R-squared from regressing interest rates on each factor separately equals the total R-squared from regressing interest rates on both factors at once. As we see from Figure 6.A.3, the target factor explains more at the lower horizons, while the path factor explains more at the longer horizons. At the shortest horizon, the target factor explains everything by construction.

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